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An Evaluation of Positive Displacement Cryogenic Volumetric Flowmeters

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An Evaluation of Positive Displacement Cryogenic Volumetric Flowmeters

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PREFACE

The comments of this report, the use of descriptive phrases and diagrams, or the actual performance of the meters do not in any way constitute endorsement either expressed or implied by the National Bureau of Standards.

The authors want to thank Dr. Brian Joiner and Dr. Peter Tryon of the Statistical Engineering Laboratory of NBS for their assistance in this test program. Test schedules they prepared and their assistance in analyzing the data have been invaluable.

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AN EVALUATION OF POSITIVE DISPLACEMENT CRYOGENIC VOLUMETRIC FLOWMETERS

J. A. Brennan, J. W. Dean, D. B. Mann, and C. H. Kneebone

The National Bureau of Standards (NBS) and the Compressed Gas Association (CGA) have jointly sponsored a research program on cryogenic flow measurement. A cryogenic flow research facility was constructed and was first used to evaluate commercially available cryogenic flowmeters operating on a positive displacement principle.

The operation and the accuracy of the flow facility is briefly described. The performance of the flowmeters on liquid nitrogen is described by reporting the precision and bias of the meters before and after an 80-hour stability test and by defining the existence of temperature, flow rate, subcooling, and time order (wear) dependencies.

Meters were evaluated with flow rates ranging from 0.00126 to 0.0063 m^3/s (20 to 100 gpm), pressures ranging from 0.22 to 0.77 MN/m^2 (32 to 112 psia), and with temperatures ranging from 72 to 90 K.

Key Words: Cryogenic; flow; flowmeters; liquid nitrogen; measurement; positive displacement.

1. Introduction

The National Bureau of Standards and the Compressed Gas Association have jointly sponsored a program of cryogenic flow research. A dynamic gravimetric flow facility has been constructed at NBS Boulder, and flowmeters operating on several principles have been evaluated. This report describes the results of the evaluation of volumetric cryogenic flowmeters operating on the principle of positive displacement. Liquid passing through the meters causes a mechanical device to sweep through a fixed volume. The mechanical device is coupled to a register indicating the total amount of liquid metered. The meters are further classified as to the type of positive displacement element used. This report gives the performance and operating methodology of four types of cryogenic volumetric flowmeters (all that are currently commercially used in the U. S.) operating with the positive displacement principle metering liquid nitrogen.

Meters were submitted to test as a result of recommendations from a joint meeting of the Compressed Gas Association Subcommittee on Cryogenic Liquid Flowmetering and the National Bureau of Standards, Cryogenics Division. The meters submitted for testing were intended to be representative of those currently used in industry. The results presented in this report only show the capability of each individual meter tested to measure flow of liquid nitrogen.

2. Cryogenic Flow Research Facility

A continuous flow loop has been constructed that allows the dynamic gravimetric measurement of liquid nitrogen flow. The continuous flow loop, shown schematically

in figure 1, allows the establishment of constant pressures, temperatures, and flow rates over a long period of time. Liquid is pumped out of the catch tank through a heat exchanger where the pump and heat energy are removed. Liquid then passes through the test section, weigh tank, and back to the catch tank. A measurement is taken by closing the flow diverter valve, weighing the fluid that passes through a meter under test located in the test section, recording the meter registration, and timing the test interval. When the tank is filled to a preset level the flow diverter valve is opened automatically without interrupting the flow. A more complete discussion of the design of the facility is given by Dean [1969].

The principle operating criteria of the flow research facility during the period of positive displacement meter evaluations were:

1) Ability to establish and maintain thermal and pressure equilibrium during test.

2) Operation with temperatures ranging from 70 to 90 K and with pressures from 0.172 to 0.793 MN/m^2 (25 to 115 psia).

3) Usable weigh tank volume from 0.189 to 0.379 m^3 (50 to 100 gallons).

4) Flow rates are presented in mass units of kg/s for uniformity and cover the volume flow range from 0.00126 to 0.0063 m^3/s (20 to 100 gpm).

At this time the uncertainty of the measurement of total mass flow is estimated to be ±0.18 percent. This figure includes an allowance of ±0.12 percent for the known sources of systematic errors, plus an allowance of ±0.06 percent for random error. The estimated uncertainty due to the random error is based on three times the standard deviation calculated from 23 applications of the calibrated masses over a period of three months.

When volumetric meters are evaluated, the liquid nitrogen density must be determined in order to compare the meter reading with the flow facility. The liquid density is calculated from the state equation of nitrogen given by Strobridge [1962] for the measured temperature and pressure. In the United States the Compressed Gas Association has adopted the saturated liquid values calculated by the Strobridge equation. The uncertainty contributed to the liquid density from the error in the pressure and temperature measurement is ±0.03 percent. Using the state equation as a density reference, the uncertainty in the reported volume flowmeter performance is estimated to be ±0.184 percent. This value is calculated by adding in quadrature the uncertainties in the density, contributed by the pressure and temperature measurement, to the systematic uncertainties of the mass measurement and adding the result to the random error.

In addition, there is a significant uncertainty associated with the state equation. Strobridge fitted his state equation to the saturated liquid properties of Mathias [1914].

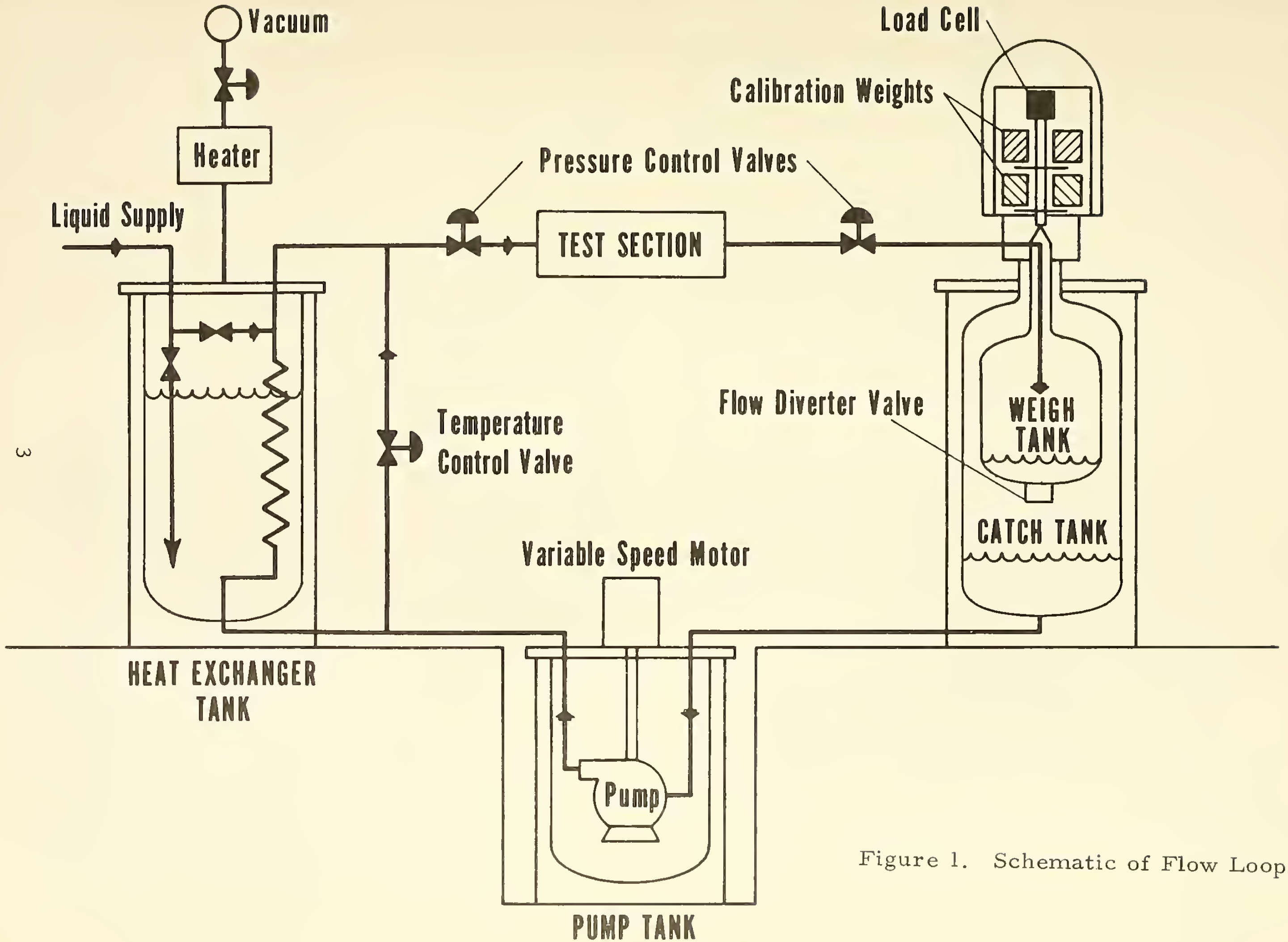

Figure 1. Schematic of Flow Loop.

More recent work by Streett [1968] gives saturated liquid molar volumes that are about 0.3 percent greater than those of Mathias. Molar volumes measured in the subcooled liquid near saturation by Terry [1969] support the data of Streett. These new density data are within the uncertainty of ±0.39 percent for density claimed by Strobridge.

The uncertainty in the state equation may be included in the estimate of the uncertainty of the reported meter performance and results in an estimated uncertainty of ±0.47 percent. This value is calculated by adding ±0.39 and ±0.12 in quadrature and adding the result to the random error. It should be realized that the largest contributor to this uncertainty is due to the uncertainty in the liquid nitrogen density. However, when the objective is mediation between seller and buyer, where both have accepted the same values of density, the estimated uncertainty of ±0.18 percent should be used. The contributions of the pressure and temperature measurements error are negligible.

This uncertainty statement applies for the specified operating criteria and for the ideal condition where operational or equipment malfunctions are not present. This accuracy statement should be considered provisional as the evaluation of the flow facility capability is in progress. For example, the random error reported is based on static measurements. Dynamic evaluation of the random error is planned in the future. When the results of these tests become known the uncertainty statement will be updated as required.

The positive displacement meter evaluation was the first work done with the flow facility; consequently, operational procedures and equipment were being evaluated to some extent during the meter tests. Those data that appear suspect and whose cause for abnormality have been traced to an operational or equipment malfunction have been removed. The remaining data are believed to be representative of the meter performance and are thus analyzed. The frequency of malfunctions has been reduced as operational experience has been gained.

3. Method of Meter Evaluation

The performance of the meter is evaluated by comparing the amount of liquid registered by the meter over the test interval to the liquid mass accumulated in the weigh tank for a wide range of liquid conditions. The mass of liquid registered by the volumetric meters tested is calculated from the expression:

$$M_R = P \cdot V_K \cdot \rho \tag{1}$$

where

M_R = mass registered by meter (kg)

P = pulses, or meter counts

V_K = volume meter factor (m^3/pulse)

ρ = liquid density (kg/m^3).

The meter count is obtained by attaching an electronic pulser to the meter register when the meter is not so equipped. Photocells and magnetic switches have been used. The test draft is started and terminated on integer counts. The volumetric meter factor, V_K, is the volume registered by the meter per count.

There are two classes of registers in common use with volumetric meters. The first class registers the swept volume of the meter. The meter factor is determined by dividing the volume registered by the number of pulses generated during the same time interval. The calculation of the factor is made by averaging the pulses over a large volume displacement of the meter. The second class of registers indicates mass flow. This meter register assumes a design liquid density. The volumetric meter factor is found by dividing the mass registered per pulse by the design density.

In the United States, the unit of volume commonly registered is the U. S. gallon (0.003785412 m^3). The unit of mass is given in terms of volume at a defined density, for example, as a cubic foot of gas at normal temperature and pressure. The CGA defines the normal temperature and pressure (NTP) to be 294.27 K (70°F) and 0.1013 MN/m^2 (one atmosphere).

The mass registered is then compared to the mass accumulated in the weigh tank and the percent deviation calculated as follows:

$$\text{percent deviation} = \frac{M_R - M_{NBS}}{M_{NBS}} \cdot 100 \qquad (2)$$

where

M_R = mass registered on the meter

M_{NBS} = mass measured by NBS.

The Cryogenic Liquid Flowmetering Subcommittee of the CGA and NBS jointly decided to subject each meter to three types of test. These tests are a rangeability test, a long term stability test, and a boundary test.

The purpose of the rangeability test is to subject the meter to a variety of conditions and to observe the response of the meter to these conditions. This test was statistically designed so the effect of various factors could be separated. The temperature range explored was from 80 to 90 K in 2.5 K increments. The pressure range was from 0.427 to 0.772 MN/m^2 (62 to 112 psia) in increments of 0.086 MN/m^2 (12.5 psi). Flow rates depended on the meter capacity with the flow range being divided into four

increments. A schedule of variables, based on a table of random numbers, was selected for all meters. A typical schedule is given in appendix A.

An 80-hour stability test was designed to determine the effect of wear on the meter performance. The stability test was run at flow rates near the maximum rated capacity and at a convenient temperature near 80 K in approximately eight-hour shifts with the meter being allowed to warm up overnight.

The boundary test was performed with the liquid conditions at the bounds of what the Cryogenic Liquid Flowmetering Subcommittee and NBS judged to be well beyond the normal operating range for most meters and within economic operation of the flow facility. The upper boundary was set at a pressure of 0. 772 MN/m^2 (112 psia) with the temperature varying from about 72 to 85 K. The lower pressure boundary was set at 0. 22 MN/m^2 (32 psia) with the temperature ranging from 72 K to a temperature as close to the saturation temperature as could be obtained without excessive cavitation occurring in the meter. The purpose of these bounds was to establish a wide range of liquid subcooling conditions.

A first rangeability test is conducted for each type of meter before the 80-hour stability test is performed, and a second rangeability test is generally performed at the conclusion of the stability test. The boundary test is performed before the start of the stability test.

A ten percent overspeed test was performed after the second rangeability test for two types of meters. This test consisted of operating the meters at ten percent over their rated capacity for four hours. However, this test was abandoned when it did not prove to be useful.

4. Data Analysis

The criteria for meter performance are the precision and bias of the meter and the existence of flow rate, temperature, subcooling, and time order (an indication of meter wear) dependencies. A mathematical model was used to fit the data obtained from the rangeability tests and the results are reported in the appendices. The mathematical model used was:

$$y = \mu + aT + bT^2 + c\dot{m} + d\dot{m}^2 + e\theta$$

where

y = bias in percent

μ = mean of the bias in percent

T = temperature in kelvins K

$\dot{m}$ = mass flow rate in kg/s

θ = time order term.

The coefficients give an indication of the dependency of the corresponding terms and are given for each rangeability test when they are significant. Pressure was not included in the model since the scatter plot of pressure did not indicate a dependency. For most meters there is little wear occurring over the period of six to eight hours required to perform the rangeability test; however, the time order term originally included was found to be significant in only one case. In the case where terms do not prove to be significant, they were removed from the model. In the majority of cases, reduced linear models have been used.

A subcooling term has not been included in the model since the rangeability test was designed to avoid a subcooling dependency. The subcooling dependency may be seen by examining the boundary test data. Similarly, the effect of wear is best seen by examining the stability test data.

The precision of the meters is calculated from three times the standard deviation of the residuals obtained after fitting the mathematical model to the rangeability test data. The bias of the meter was obtained by evaluating the mathematical model at the rated maximum flow rate of the meter under test at a temperature of 80 K. The bias may also be calculated from the mathematical model for any desired combination of parameters that are within the range of the experimental data.

5. Meter Performance Summary

The record of the meters tested is given in table 1. Ten positive displacement meters were installed in the test section. Two or three meters of each type were submitted. Where possible, each meter was subjected to a first rangeability and boundary test with one of the type being subjected to the stability and second rangeability test. Exceptions to this plan occurred for meter A and meter G. Meter A was the first meter tested primarily for the purpose of evaluating the facility before a meter test plan was formulated. The stability of meter A is reported since it was run in excess of eighty hours. However, the first rangeability and boundary test of meter F is reported for the same type of meter. The performance of meters A and F are similar. Meter G failed to turn over during the preliminary test and little useful data were obtained.

A detailed description of the meters and their performance is given in the appendices. A summary of the meter performance is given in table 2. The precision reported is three times the standard deviation calculated from the data taken during the rangeability tests. The precision at the start is calculated from the first rangeability test taken before the stability test, while the precision at the end is calculated from the second rangeability test taken after the stability test. The meter bias is reported for each test. The volume metered is the amount of liquid metered during the stability test.

Table 1. Positive Displacement Meter Test

Test Meter	Meter Type*	1st Range	Boundary	Stability	2nd Range
A	SIE			X	
B	SIM	X	X		
C	SIM	X	X		
D	SIM	X	X	X	X
E	OP	X	X	X	X
F	SIE	X	X		
G	RV				
J	OP	X	X		
L	RV	X	X	X	X
M	OP	X	X	X	X

*SIE - Screw Impeller with an electrical counter
SIM - Screw Impeller with a mechanical counter
OP - Oscillating piston
RV - Rotating vane

Table 2. Meter Performance Summary

Meter Type	Screw Impeller Electric Register		Screw Impeller Mechanical Register	Rotating Vane	1-Inch Oscillating Piston	$1\frac{1}{2}$-Inch Oscillating Piston
Meter	A	F	D	L	E	M
Precision (3σ) at Start, %	±0.66	±0.69	±0.33	±0.69	±1.7	±0.63
Precision (3σ) at End, %	±0.51		±0.48	±2.1	±1.5	±0.54
Bias at Start, %	+1.17	+1.59	+0.28	+1.04	+2.2	+1.33
Bias at End, %	+0.55		+0.50	-4.8	+1.6	+0.61
Volume Metered m^3 (gal)	1249 (330,000)		870 (230,000)	1333 (352,219)	908 (240,000)	1225 (323,800)
Maximum Flow Rate m^3/s (gpm)	0.0025 (40)	0.0025 (40)	0.0032 (50)	0.0063 (100)	0.0032 (50)	0.0044 (70)
Minimum Subcooling, K	**	5*	5*	3	5	5

* Cavitation occurred at 4 K.

** See page B-2

NOTE: This table is a highly condensed summary of the results of an extensive testing program. In this table it has not been possible to present some information that may be important in some applications. For example, some of the meters tested had statistically detectable temperature and flow rate dependencies. These additional details are presented in the appendices of this report.

The minimum subcooling at which the meters were operated is reported. Vapor was formed in two of the meters by cavitation occurring, resulting in overregistration from two to three percent. Operation with one or two more degrees of subcooling returned the meter performance to normal. Noticeable cavitation did not occur with three of the meters.

6. Flowmeter Methodology

Considerable experience in meter installation and operation was gained during the process of obtaining the reported data. The more important aspects of this experience may be of value to those who buy and sell cryogenic liquid products.

Cryogenic liquids are commonly sold on a mass basis. The unit of sale in the United States is the gas equivalent of the metered liquid in terms of the cubic foot ($0.02832\ m^3$) at N. T. P. or the U. S. gallon ($0.003785\ m^3$) of liquid at the normal boiling point. Operation of volumetric meters as mass meters requires the assumption that the meter is operated at a specified design density. In order to know the accuracy of a liquid billing based on volumetrically metered liquid, it is necessary to know the uncertainty of the meter at the density which the delivery is made.

It is current practice with liquid transports to install a meter at the discharge of a liquid pump. The meter and pump are primed prior to delivery to the customer by gravity feed out of the liquid tank. The gas generated by priming is vented to the tank ullage space, thus no product is lost. The result is to raise the pressure and to put heat energy into the system. During the day several deliveries may be made from a single transport. The pressure and temperature and thus the density of the liquid will be changing during the day.

It is necessary to examine the range through which the density may vary. The isothermal compressibility of liquid nitrogen can be calculated from Strobridge [1962]

$$\frac{1}{\rho}\left(\frac{\partial \rho}{\partial P}\right)_{T\,=\,80\ K} = 0.003\ \mu m^2/N\ (\text{or } 0.0022\%/\text{psi}).$$

However, the temperature dependency calculated from the volume expansivity is

$$\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_P = 0.006\ K^{-1}\ (\text{or } 0.6\%/K).$$

If the meter is calibrated at a known temperature and pressure and operated at the same temperature, but at a pressure that is different by $1.379\ MN/m^2$ (200 psi), then a difference in density and meter registration of 0.44 percent may be expected.

A much stronger effect occurs with changes in liquid temperature. When the transport is filled with liquid nitrogen in the morning, the liquid will normally be near a saturation temperature of 80 K at a pressure of approximately 0.1379 MN/m^2 (20 psia). Hopefully, the temperature will rise only one or two K during the day as the pressure rises. The temperature can rise much more depending on thermal performance and relief valve setting of the tank. Assuming that the relief valve is set at 0.207 MN/m^2 (30 psia) and the tank has a poor enough thermal performance to allow the liquid to become saturated at this pressure, then the liquid temperature will rise to 84 K. The liquid density will decrease 2.4 percent. If the meter was designed to operate at 82 K, then the meter will overregister by 1.2 percent.

Current practice is to assume an average liquid temperature of about 82 ±1 K and to design the meter to operate at this temperature. Liquid density and temperature readings are not taken. Under ideal conditions of using a perfectly accurate meter and a liquid tank with good thermal performance, the uncertainty of the measurement of the total amount of liquid is not better than ±0.6 percent because of the variability in liquid density. The bias and imprecision of the meter must be added to this value to obtain the total uncertainty of the measurement. Meter precisions are given in this report. The bias of the meter will depend on the liquid supplier's calibration facility and the diligence with which he adjusts his meters. In all cases the meters supplied for evaluation in this work overregistered (from +0.28 to +2.2 percent).

Some meters are installed on tank trucks with permanent piping into the meters. Often the meter is silver soldered or welded in place. Thus, the entire meter is not conveniently removable as a unit. When meter service is required, the register and positive displacement elements are unbolted and removed from the bowl or shell that remains attached to the piping on the truck.

The positive displacement element is repaired and may be recalibrated on a test stand using another bowl. After recalibration, the meter is placed in stock for eventual use with still another bowl. This approach is convenient from the viewpoint of servicing meters, but it does not allow optimum meter accuracy.

The above type of meter operation assumes the interchangeablity of meter positive displacement elements and meter bowls. Our experience is that operation of the same positive displacement element in different bowls can yield a different average value, or bias. This is caused by a variability of seal performance between different combinations of positive displacement elements and bowls. Figure 2 shows a typical hidden seal. Tightening the bolts on top of the bowl makes both a top seal that prevents liquid from

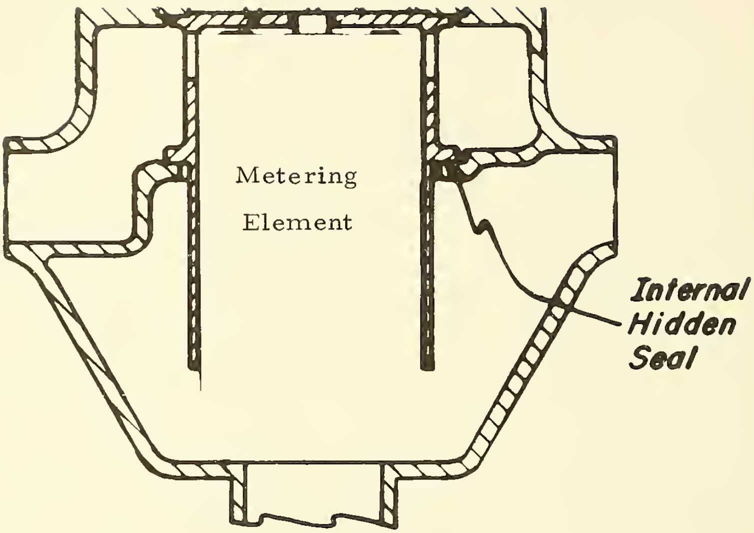

Figure 2. Hidden Seal.

leaking out around the counter support and a bottom seal that is meant to prevent liquid from bypassing the metering element. There is no way to directly check the bottom seal for leakage. We have observed differences in biases of about 1/2 percent when operating the same positive displacement element in different bowls. Leakage through this seal will result in underregistration.

A similar problem exists with meter registers. For ease of maintenance, it is desirable to interchange meter registers with positive displacement elements. However, meter performance is a function of the torque loading of the register. We have observed drastic changes in meter performance by changing meter registers. At low flow rates liquid will leak through the positive displacement element if the register is restrained. We have observed underregistration by more than ten percent at low flow rates caused by a malfunctioning register.

The meters should be operated with sufficient subcooling to prevent the formation of vapor in the liquid line and in the meter. Tests performed with the liquid approaching the saturated condition have shown a degradation of performance. There is a tendency toward an increase in imprecision and overregistration. In some meters this is a gradual trend, while in others overregistration starts suddenly when 2 or 3 degrees of subcooling are reached. In all cases vapor formation in the meters and the resulting overregistration may be avoided by operating with ten degrees of subcooling at the meter inlet.

Once adequate subcooling is achieved and density corrections are made according to the state equations, the volumetric flowmeters tested are not strongly affected by the density or temperature of the liquid nitrogen metered. When the temperature is held constant, changing the operating pressure had no apparent effect on meter performance. However, changing the liquid temperature has a slight but noticeable effect, in addition to the density correction, according to the state equation. Some meters show a change in bias as much as 1/2 percent when the liquid temperature is varied from 72 to 90 K. It is not clear if this is caused by the density or temperature change.

Positive displacement volumetric flowmeters are subject to wear. Wear has manifested itself in three ways: as a trend toward overregistration with increasing time, a trend toward underregistration with increasing time, and a trend towards an increased imprecision. One meter showed a 1/2 percent change in bias with as little as 56.8 m^3 (15,000 gallons) of liquid metered. More typically the meters can register some 1136 m^3 (300,000 gallons) before this much change in the bias occurs.

Some of the meters tested are capable of operation with an uncertainty between ±1/2 to ±1 percent in the volume registered. In order to achieve this performance it is

necessary to accurately calibrate the meters as a unit, to know the meter performance through the operating temperature range, and to limit the total amount of liquid that may be metered between calibrations. If mass is registered, then a correction must be made to account for the difference between calibration and operating density to achieve the best meter accuracy.

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APPENDIX A. Rangeability Test Plan

The purpose of the rangeability test is to investigate the performance of cryogenic liquid flowmeters when the flowmeters are subjected to the following conditions:

1) Temperature varying from 80 to 90 K
2) Pressure varying from 0.427 to 0.772 MN/m^2 (50 to 100 psig)
3) Flow rates from 0.00126 m^3/s (20 gpm) to the maximum rated capacity in four steps.
4) Average barometric pressure of 82.7 kN/m^2 (12.0 psia).

The liquid density resulting from the chosen pressure and temperature ranges from 803 kg/m^3 (6.7 lbs/gal) to 743 kg/m^3 (6.2 lbs/gal).

In addition, it is desired to keep the subcooling, which is a function of temperature and pressure, between 10 and 20 K.

It is time consuming to increase the temperature of the flow system, so it is desired to keep temperature changes to a minimum. In addition, pressure changes must be kept at a minimum to conserve helium, but the flow rate may be changed almost instantaneously.

<u>Suggested Plan</u>

A test plan using a meter with a maximum flow rate of 0.0025 m^3/s (40 gpm) is as shown in table 1A.

Table 1A. Rangeability Test Plan

	3↑	5↓	1↑	4↑	2↓
Pressure psig 100	20	26	33	40	26
87.5	26	40	26	33	20
75	33	33	40	20	
62.5	40	20	20		
50	26	33			
Temperature K	80	82.5	85	87.5	90

The plan shown in table 1A is a 5 x 5 Latin square with a triangular portion removed due to the subcooling constraint. The numbers and arrows at the top indicate the order in which the tests are run. A schedule is set up for the convenience of the operator as follows:

Run Number	Temperature K	Pressure psig	Flow Rate gpm
1	85	62.5	20
2	85	75	40
3	85	87.5	26
4	85	100	33
5	90	100	26
6	90	87.5	20
7	80	50	26

Since setting the temperature and pressure exactly to the schedule value is quite difficult, it will suffice just to set them approximately and record the actual values achieved.

APPENDIX B. Performance of a Screw Impeller Meter with an Electric Counter (Meters A and F)

This meter is illustrated in figure 1B. Liquid is admitted to the inlet at the bottom of the meter and is first taken out the priming line to cool the meter to operating temperature. After priming, liquid flows through the strainer into the rotors and out the discharge. Liquid flowing through the rotors causes them to turn. The rotating motion is geared to an electrical pulse transmitter. Ten magnets are evenly spaced around and attached to a rotating shaft. A stationary reed switch attached to the meter housing is activated as the magnets move past the reed. The switch closure transmits an impulse to a magnetic impulse counter.

The meter supplier's specifications are:

fluid -- liquid nitrogen

maximum flow rate -- 0.00252 m^3/s (40 gpm)

maximum pressure -- 1.724 MN/m^2 (250 psia)

calibration -- ±0.5 percent on the test stand with ±2 percent field accuracy

register -- electrical, registering in 0.283 m^3 (10 ft^3) equivalent gas at N. T. P. per count or pulse.

This meter registers in mass units stated in the equivalent gas volume at N. T. P. The registration may be defined in mass units by multiplying the density at N. T. P. by the stated registration. Thus, the totalizing counter mass units are 1.1605 $kg/m^3 \times 0.28317$ $m^3 = 0.3286$ kg (0.7245 lbs) per count. The meter is designed to operate with liquid nitrogen at a density of 792.53 kg/m^3 (6.614 lbs/gal). The volumetric meter factor is the mass meter factor divided by the design density and is 0.3286/792.53 = 414.6 cm^3/pulse (0.1095 gal/pulse).

Two of the screw impeller meters with an electric counter were tested (meters A and F). Both of these meters demonstrated similar performance.

Since the meter registration is in equivalent mass units, density corrections are required to obtain the results shown in this report.

Meter F

The results of the first rangeability test run with meter F are shown by the scatter diagrams given in figures 2B, 3B, 4B, and 5B where the deviation is plotted as a function of the order, temperature, subcooling, and mass flow rate. The fit of the mathematical model to these data is given in table 1B.

Table 1B. Fit of Model to Meter F, First Rangeability Test Data

Model y = 1.59
Bias, y = + 1.59%
Residual standard deviation = ±0.23%
Number of points = 20

The coefficients for T, T^2, $\dot{m}$ and $\dot{m}^2$ were considered and found not to be significant. Thus, there are no dependencies for meter F. The precision based on three times the standard deviation is ±0.69 percent and the bias is +1.59 percent.

The results of the boundary test run with meter F are shown by the scatter diagrams of the data given in figures 6B, 7B, 8B, and 9B. The plot of deviation as a function of subcooling (figures 8B) shows a possible non-linear behavior at low subcooling. Near a subcooling of 4 K a tendency to overregister is seen. It is expected that vapor forming in the meter or flow system may be the cause. However, two points, one at 16 K subcooling and one at 28 K subcooling, overregister nearly as much as the points at 4 K and no explanation for those points has been found.

Meter A

Rather than take the three weeks required to perform a stability test on meter F, the data previously obtained with meter A is used to determine the stability of the screw impeller meter with an electric counter. Meter A was the first meter evaluated on the cryogenic flow facility; consequently, the facility was concurrently undergoing an evaluation. A faulty valve was found to be injecting helium into the liquid nitrogen during part of the operation with meter A. The data reported here were taken before the valve was installed and after the leak was repaired. Thus, those data shown in the scatter plot of figure 10B are in order, but they are not sequential because of the block of faulty data that have been removed. Temperature, subcooling, and mass flow rate ranges may be seen in figures 11B, 12B, and 13B. The data points at the lowest subcooling shown in figure 12B are at reduced flow rates.

Normally, the effect of the stability test is reported by giving the bias and precision as determined with a rangeability test performed before and after the stability test. In this case the rangeability test plan had not been adopted at the time meter A was tested. Twenty points were taken from the first and last points shown in figure 10B and analyzed as if they were a rangeability test. These data were taken over a temperature range of 77.2 to 79.2 K and a flow rate range of 1.09 to 2.07 kg/s (2.40 to 4.57 lb/s). The range of temperature and flow rate is not as wide as in the rangeability test; however, the

results are similar to those reported for meter F. Approximately 1249 m^3 (330,000 gallons) of liquid nitrogen were metered over 168 hours of operation between the first and last 20 point tests of meter A.

In the first 20 point test, two points were removed from the analysis. These points, seen at the lower left corner of figure 10B, were considered as not belonging to the data group. The fit of the mathematical model to these data is given in table 2B.

Table 2B. Fit of Model to Meter A, First 20 Points

Model $y = 1.41 - 0.027\ \theta$
where θ is the time order term
Bias at $\theta = 9$, $y = +1.17\%$
Residual standard deviation = ±0.22%
Number of points = 18

The coefficient for T, T^2, $\dot{m}$, and $\dot{m}^2$ were considered and found not to be significant. A slight dependency on order, θ, was noted. The bias in table 2B was evaluated in the middle of the data, for order $\theta = 9$. The precision based on three times the standard deviation is ±0.66 percent and the bias is +1.17 percent.

The fit of the mathematical model to the data of the second 20 point test of meter A is given in table 3B.

Table 3B. Fit of Model to Meter A, Last 20 Points

Model $y = 0.55$
Bias, $y = +0.55\%$
Residual standard deviation = ±0.17%
Number of points = 20

The coefficients for T, T^2, $\dot{m}$, and $\dot{m}^2$ and order were considered and found not to be significant. The precision based on three times the standard deviation is ±0.51 percent and the bias is +0.55 percent.

It should be noted that there is no significant change that has occurred in the precision of meter A after metering 1249 m^3 (330,000 gallons) of liquid and that the precision of meters A and F are not significantly different.

The pressure drop data for meter F are shown in figure 14B.

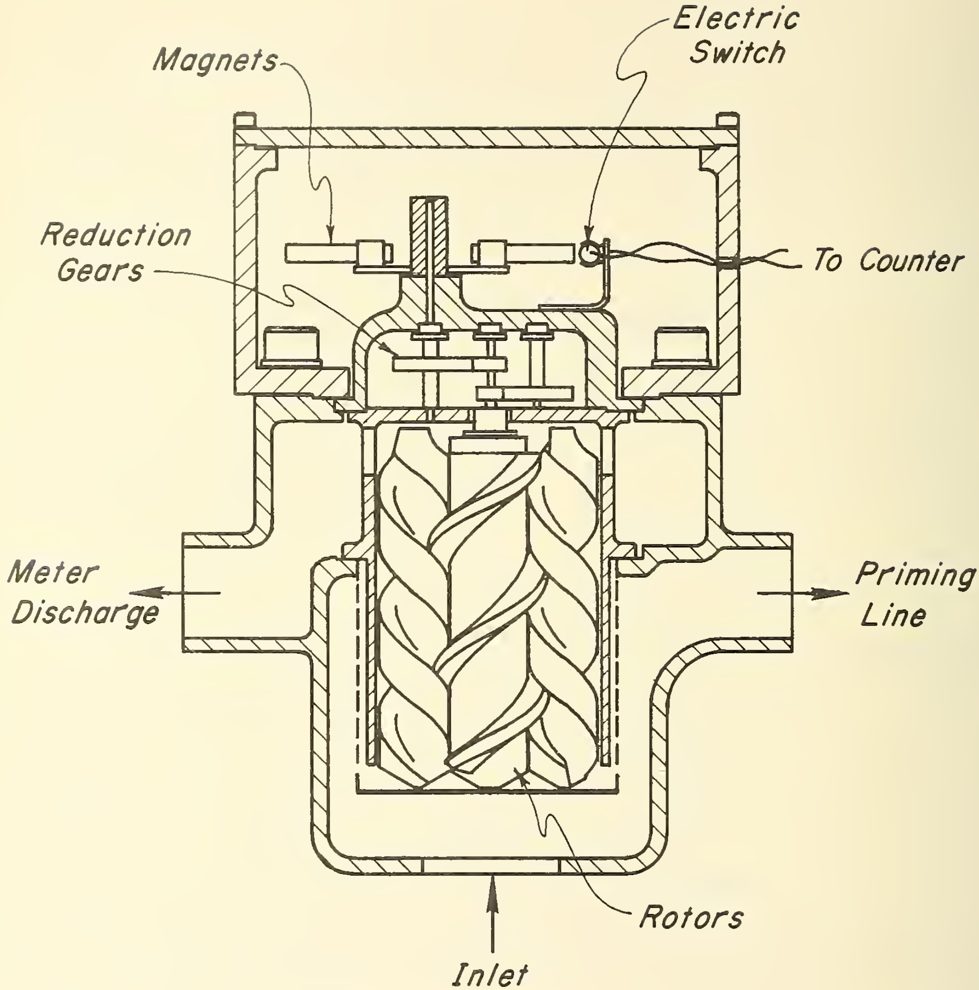

Figure 1B. Screw Impeller Meter with an Electric Counter.

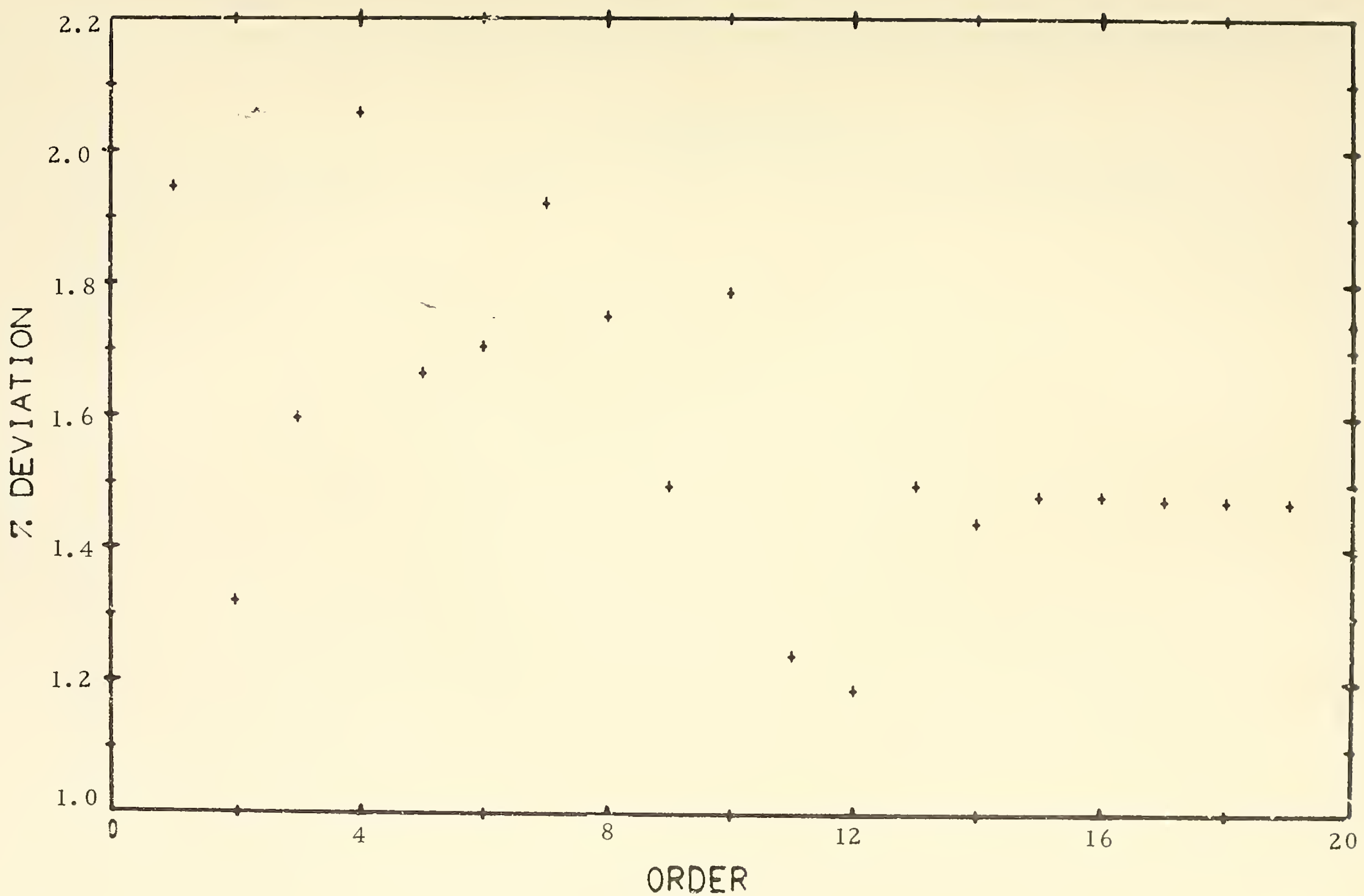

Figure 2B. Meter F, Performance vs. Order, First Rangeability Test.

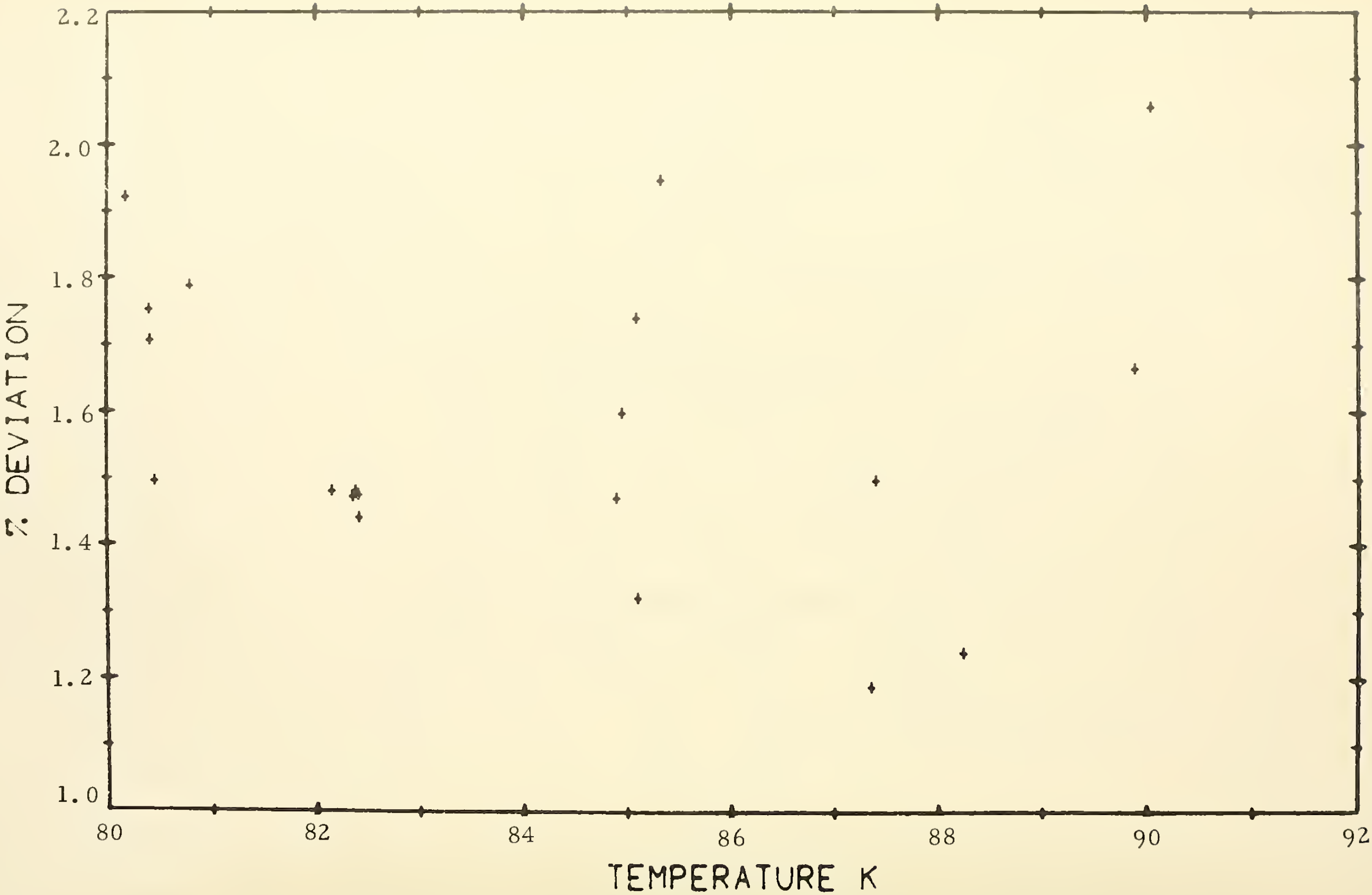

Figure 3B. Meter F, Performance vs. Temperature, First Rangeability Test.

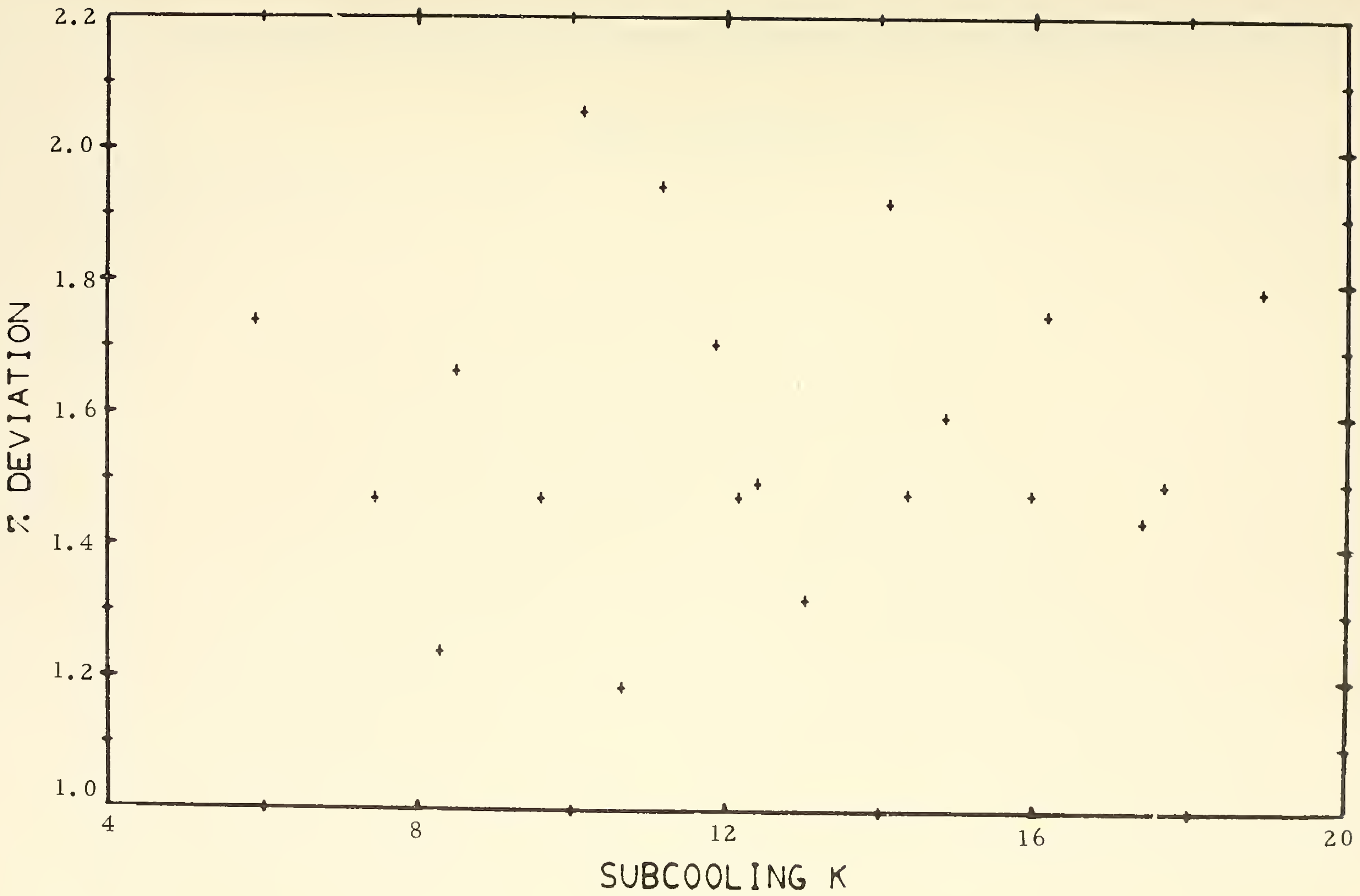

Figure 4B. Meter F, Performance vs. Subcooling, First Rangeability Test.

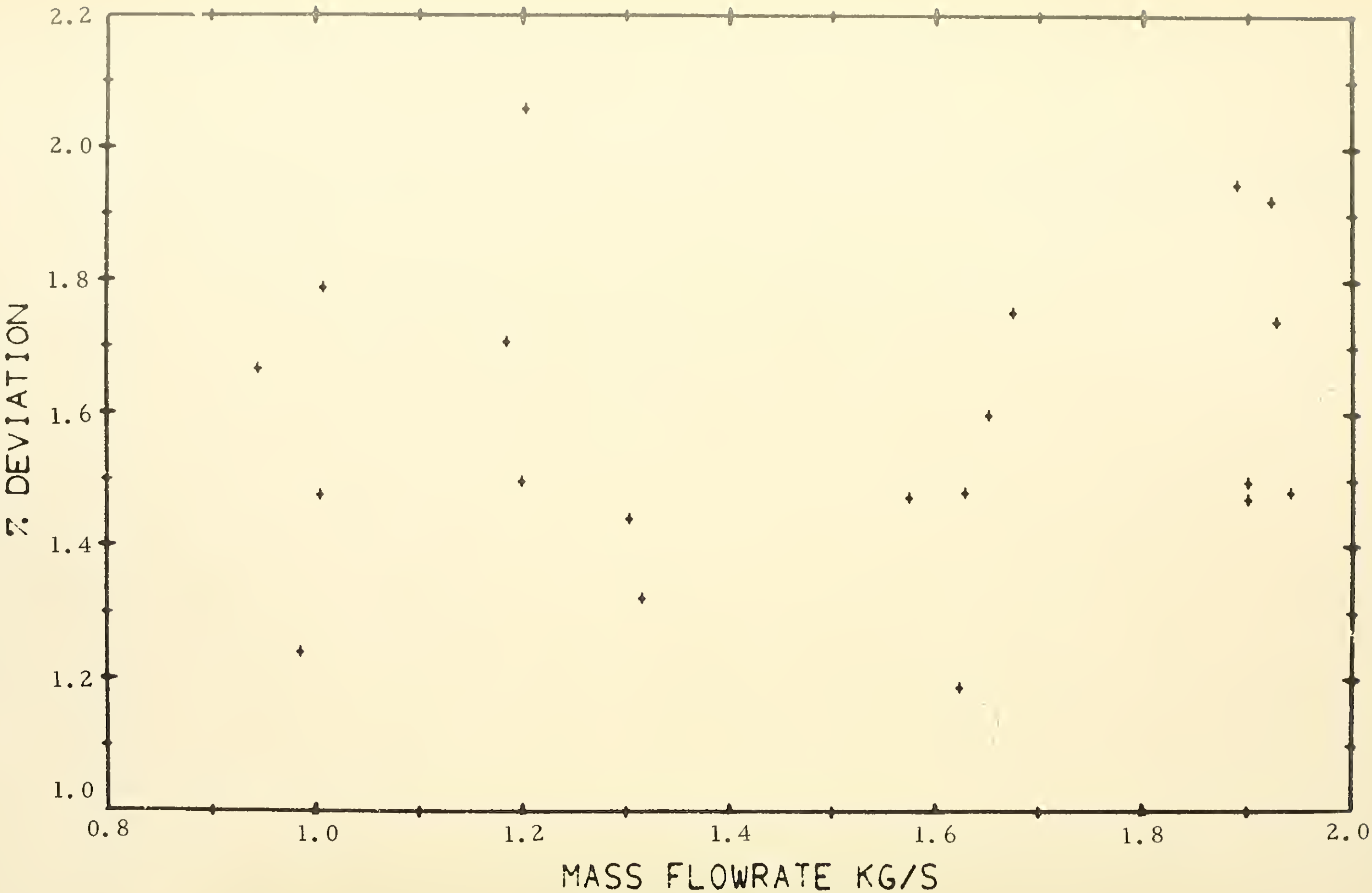

Figure 5B. Meter F, Performance vs. Mass Flow Rate, First Rangeability Test.

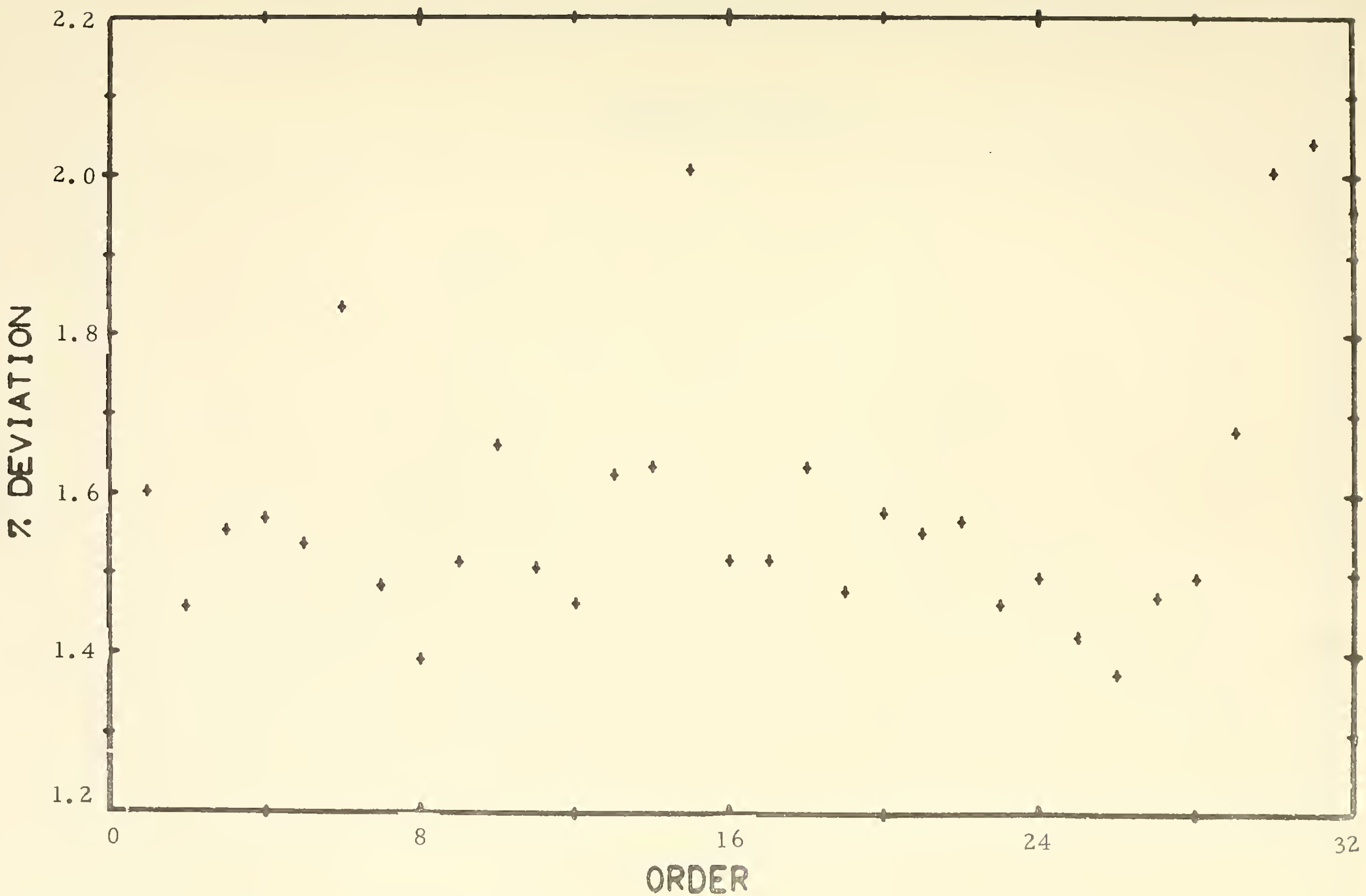

Figure 6B. Meter F, Performance vs. Order, Boundary Test.

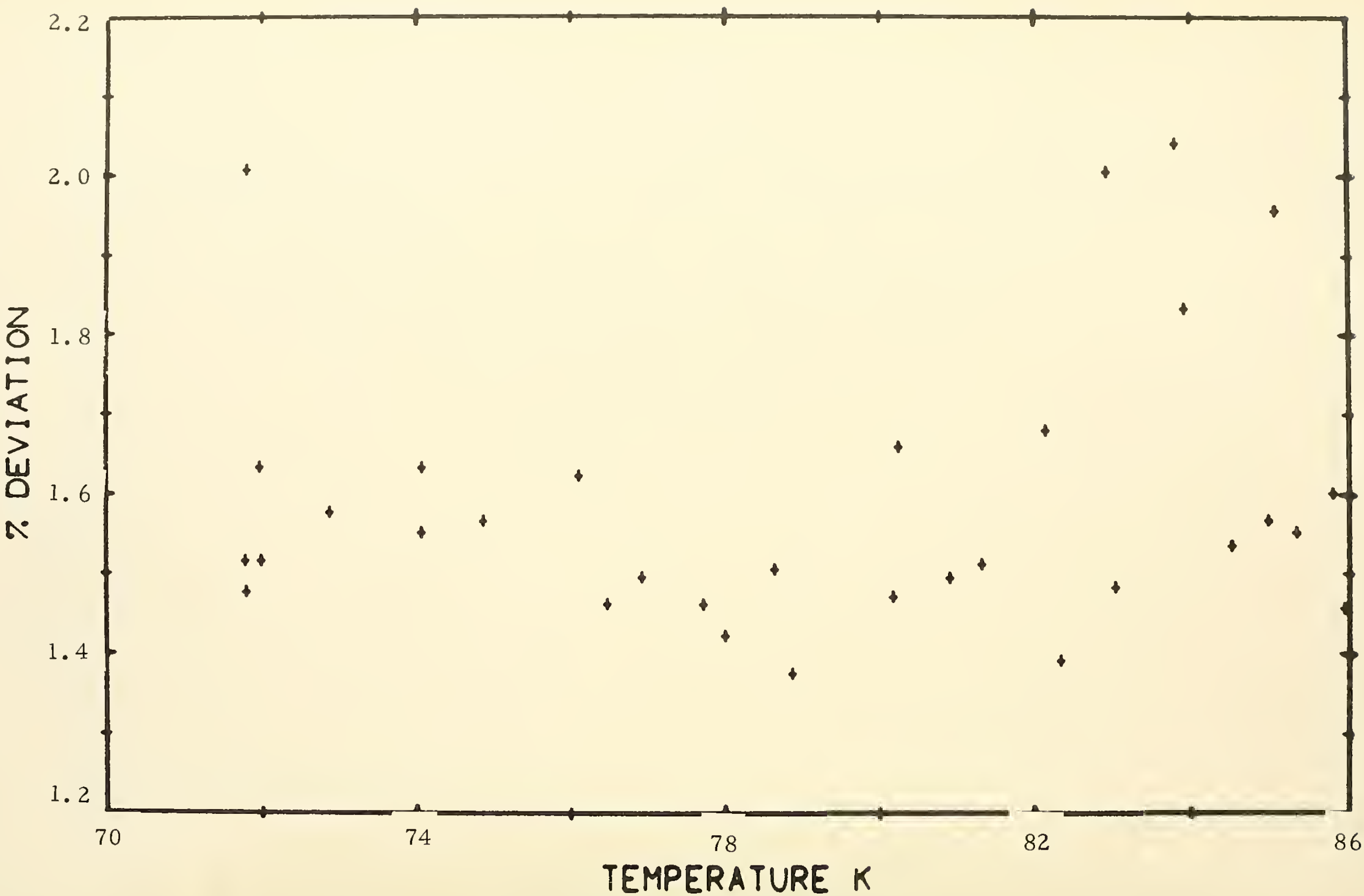

Figure 7B. Meter F, Performance vs. Temperature, Boundary Test.

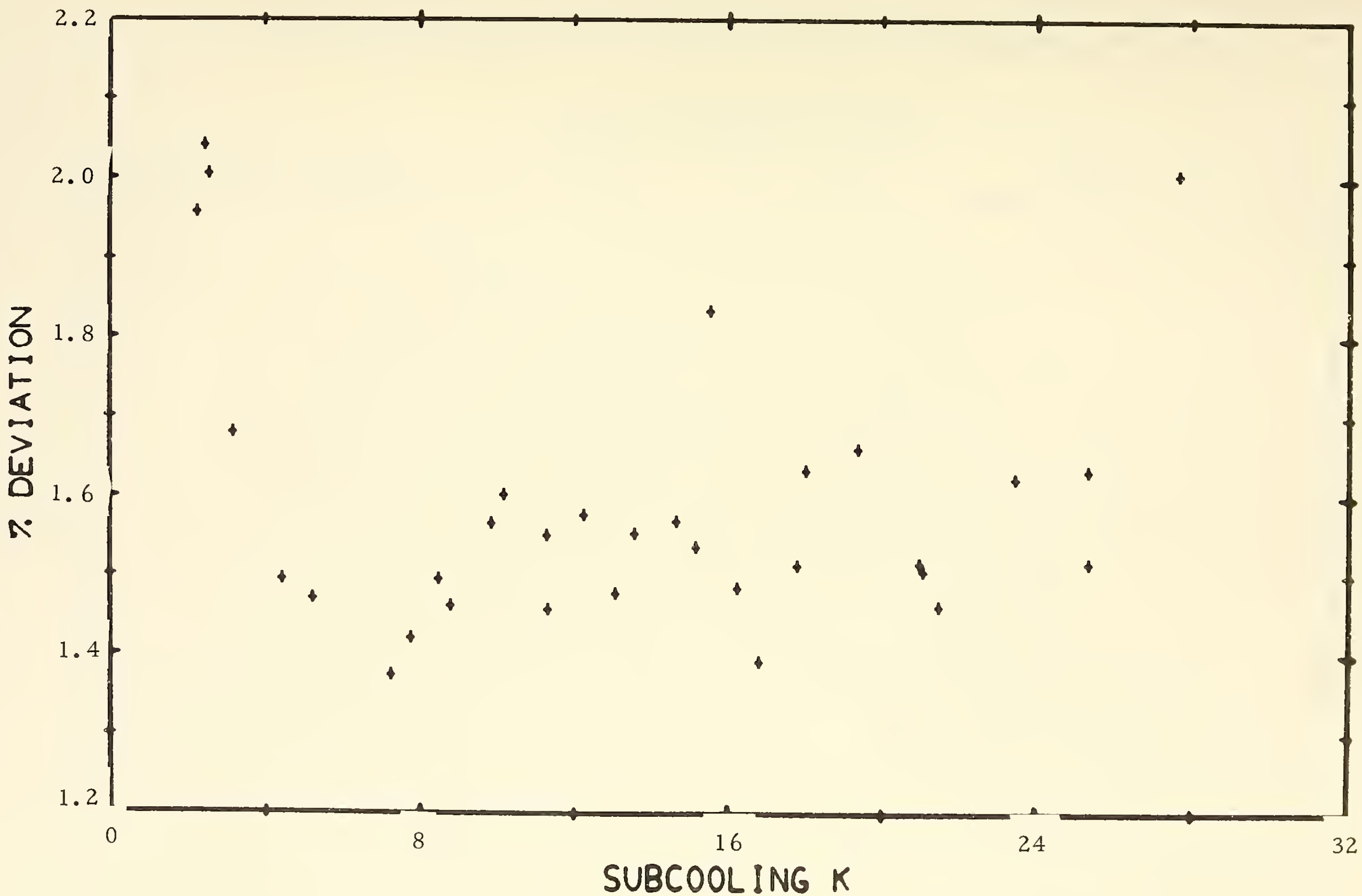

Figure 8B. Meter F, Performance vs. Subcooling, Boundary Test.

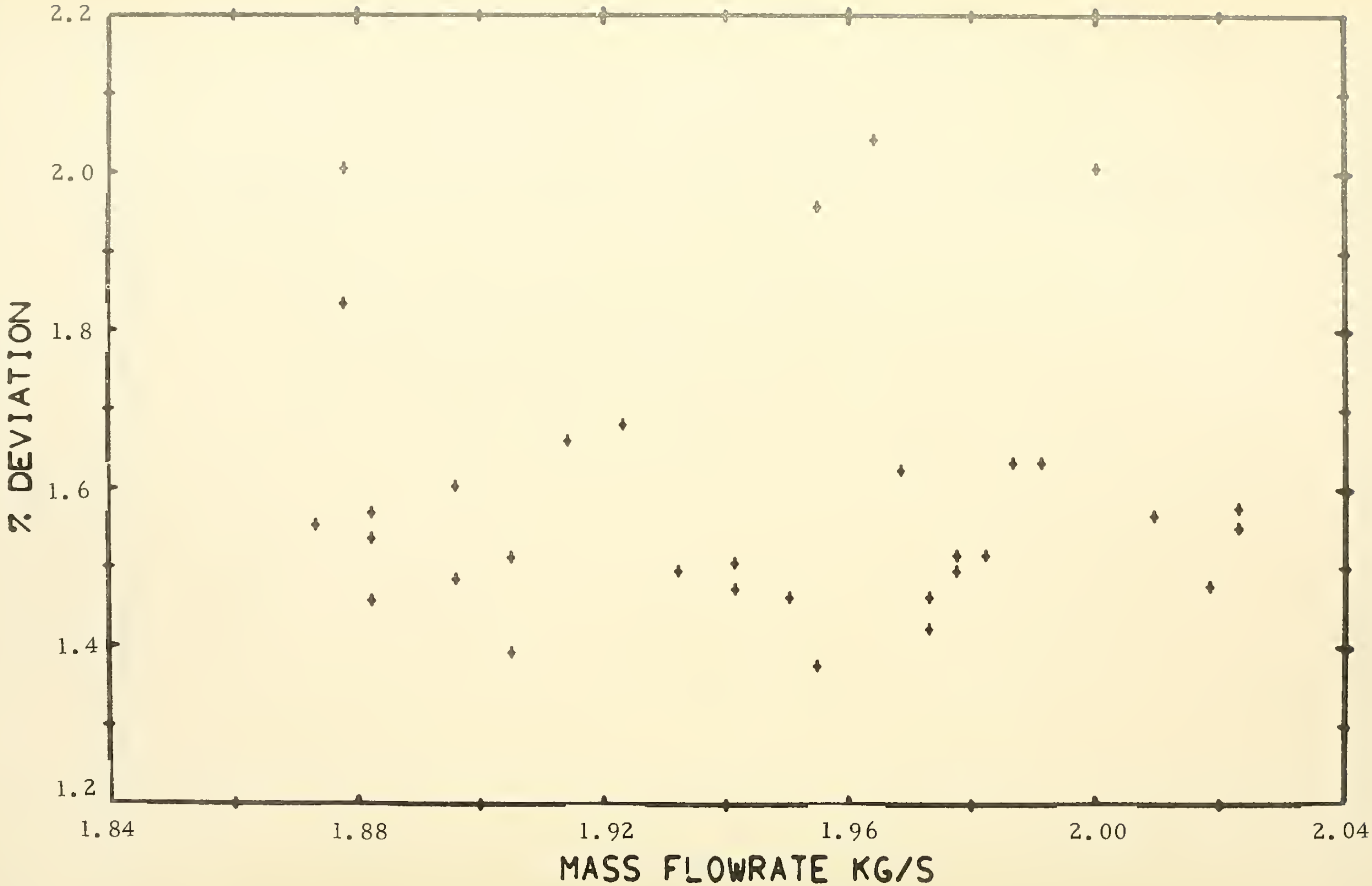

Figure 9B. Meter F, Performance vs. Mass Flow Rate, Boundary Test.

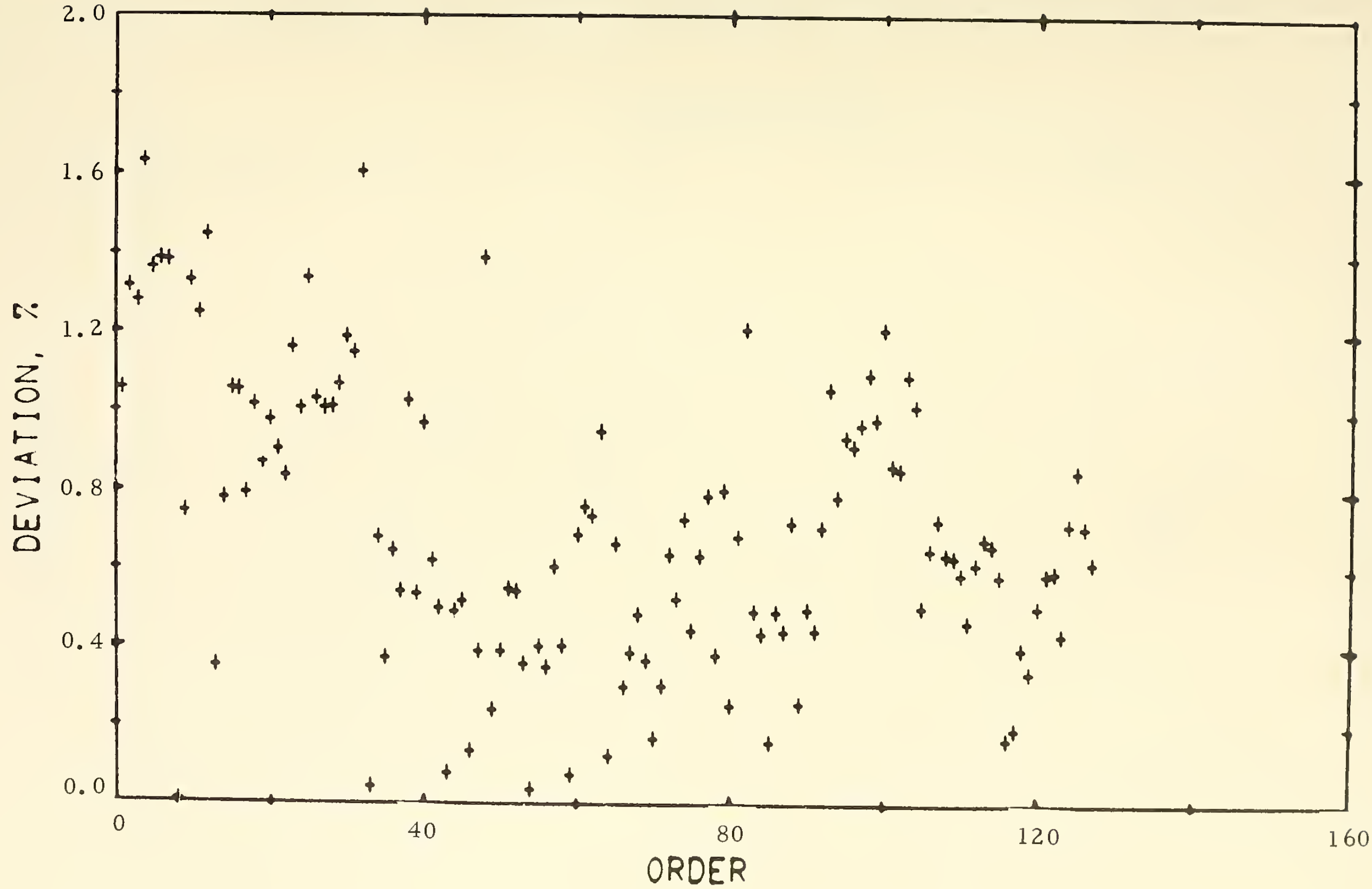

Figure 10B. Meter A, Performance vs. Order, Stability Test.

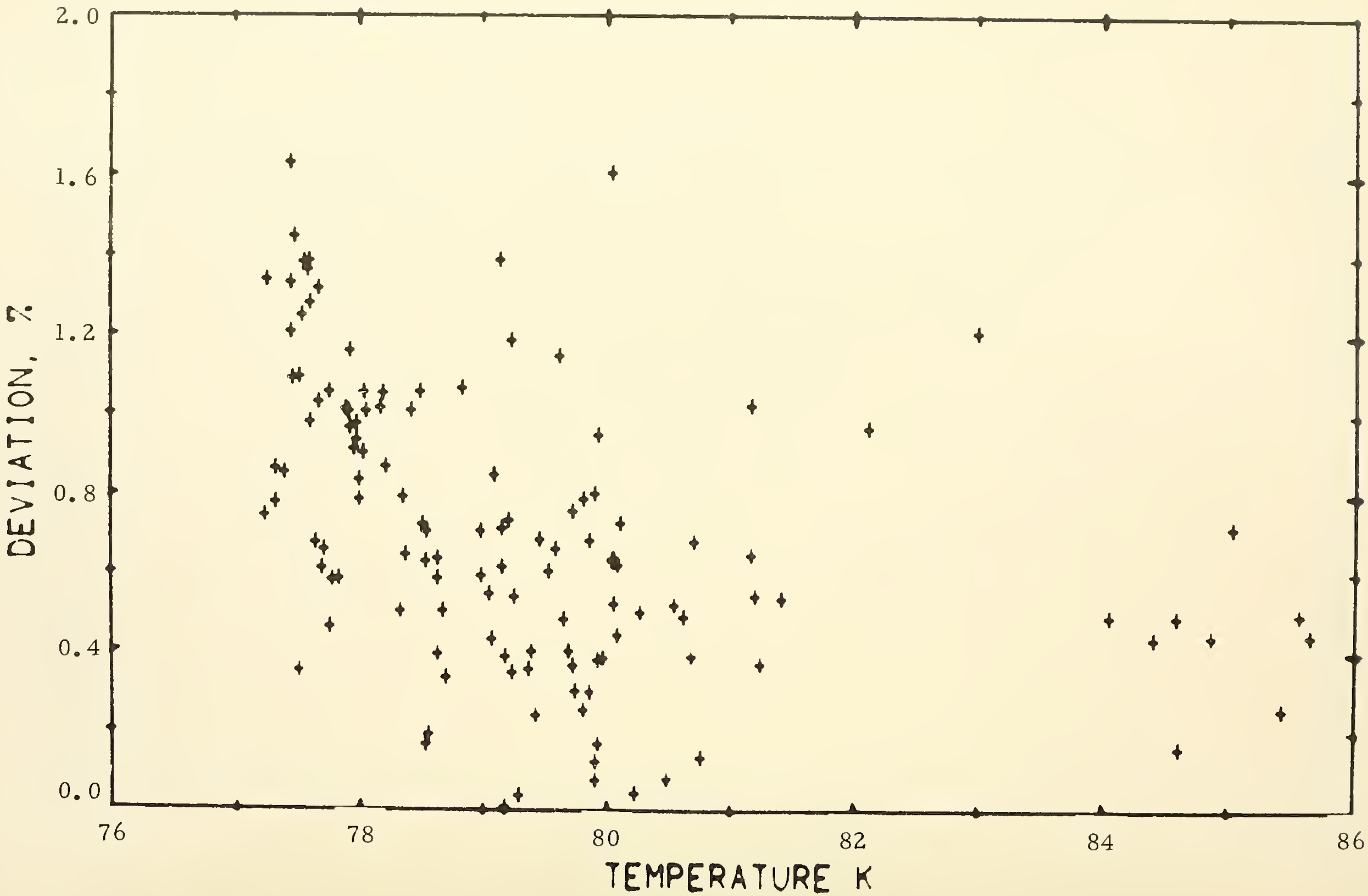

Figure 11B. Meter A, Performance vs. Temperature, Stability Test.

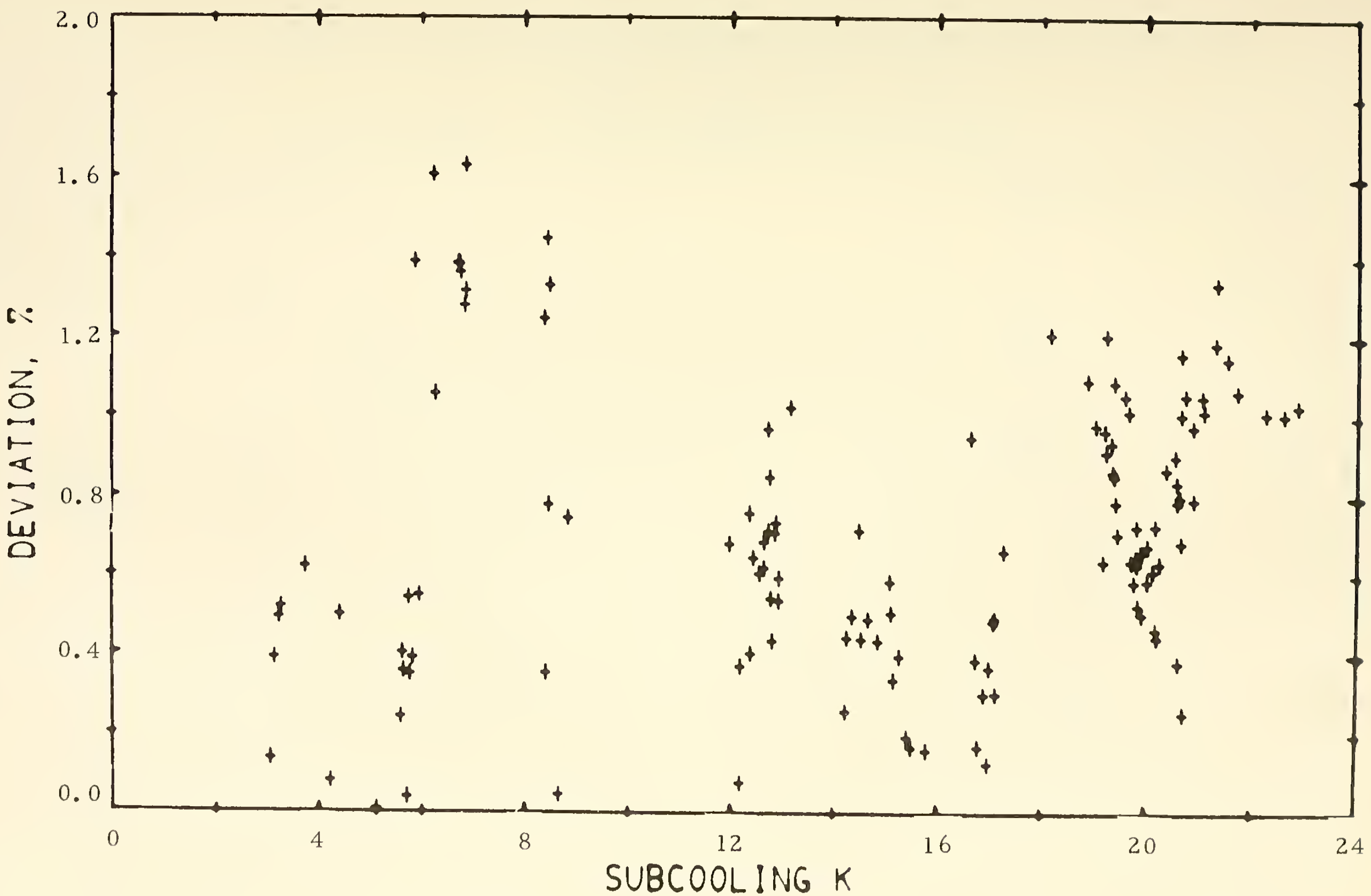

Figure 12B. Meter A, Performance vs. Subcooling, Stability Test.

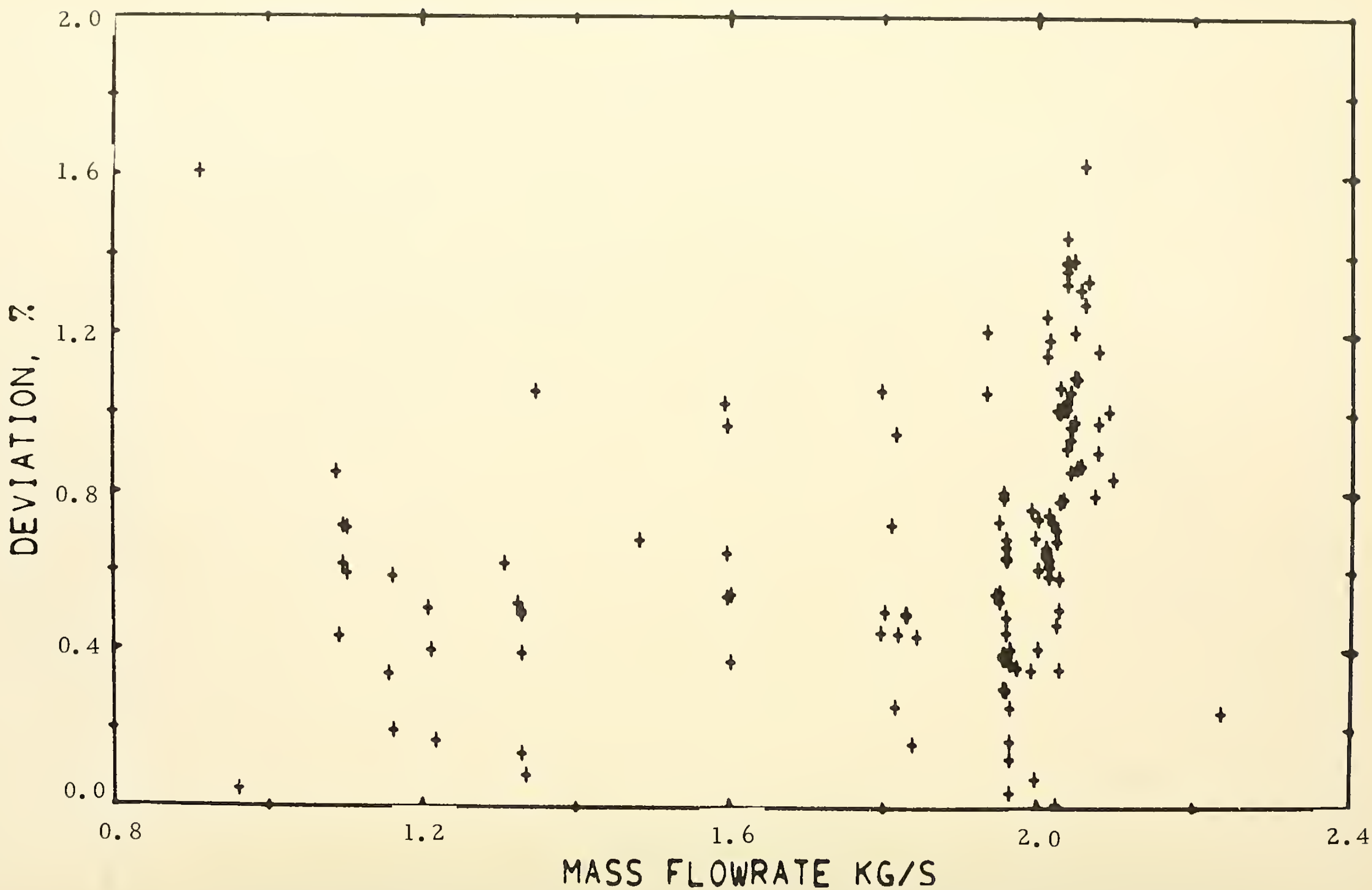

Figure 13B. Meter A, Performance vs. Mass Flow Rate, Stability Test.

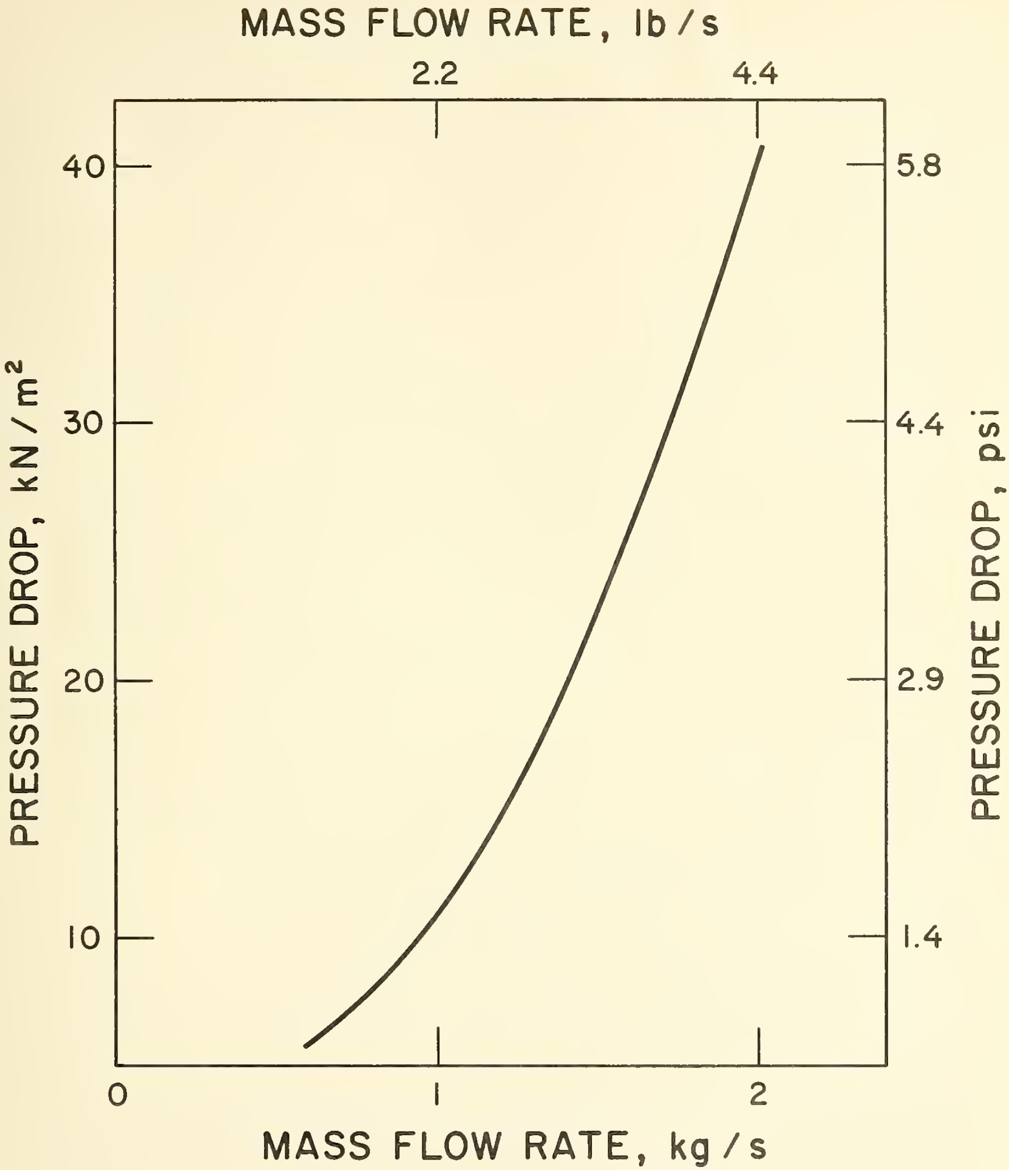

Figure 14B. Meter F Pressure Drop.

APPENDIX C. Performance of a Screw Impeller Meter with a Mechanical Counter (Meter D)

This meter is illustrated in figure 1C. Liquid is admitted to the inlet at the bottom of the meter and is first taken out the priming line to cool the meter to operating temperature. After priming, liquid flows through the strainer into the rotors and out the discharge. Liquid flowing through the rotors causes them to turn. The counter operates warm and is separated from the liquid nitrogen temperature components by a stainless steel tube. A counter on top registers the gas equivalent of the metered liquid for every 2.832 m^3 (100 ft^3) at N. T. P. A sweep hand makes a full revolution for every 2.832 m^3 (100 ft^3) registered. A photo cell was attached to the counter so the sweep hand interrupts the light source beam every revolution and generates an electrical pulse that is counted.

The specifications provided by the meter supplier are:

maximum flow rate -- 0.003155 m^3/s (50 gpm)

minimum flow rate -- 0.0006309 m^3/s (10 gpm)

working pressure -- 2.170 MN/m^2 (314.7 psia)

pressure loss at maximum flow rate -- 31.03 kN/m^2 (4.5 psi)

accuracy -- ±1% of point

repeatability -- ±0.5% of point

fluid -- liquid nitrogen at a density of 785.65 kg/m^3 (6.5566 lb/gal)

registration --

totalizing register units -- 2.8317 m^3 (100 ft^3) per revolution

N. T. P. gas (density = 1.1605 kg/m^3) (0.07245 lb/ft^3)

sweep hand units -- 0.028317 m^3 (1 ft^3) N. T. P. gas.

This meter registers in mass units stated in the equivalent gas volume at N. T. P. The registration may be defined in mass units by multiplying the density at N. T. P. by the stated registration. Thus, the totalizing register mass units are 1.1605 kg/m^3 x 2.8316 m^3 = 3.286 kg (7.245 lbs) per 100 ft^3 registered. Since the photo cell delivers a pulse for every totalizing registration unit, the mass meter factor is 3.286 kg/pulse (7.245 lbs/pulse). The meter is designed to operate with liquid nitrogen at a density of 785.65 kg/m^3 (6.5566 lbs/gal). The volumetric meter factor is the mass meter factor divided by the design density and is 0.004183 m^3/pulse (1.105 gal/pulse).

Three of the screw impeller type of meters with mechanical counters were tested (meters B, C, and D). All of these meters demonstrated very nearly the same performance. Meters B and C underwent the rangeability and boundary test only, while meter D was put through the stability test and a second rangeability test.

Since the meter registration is in equivalent mass units, density corrections are required to obtain the results shown in this report.

The data from all the tests of meter D are given in figure 2C where the deviation as a function of the order is shown. The high data group near point 60 was caused by cavitation in the meter during the boundary test.

The results of the rangeability test of meter D are shown by the scatter plots given by figures 3C, 4C, 5C, and 6C. The fit of the mathematical model to these data is given in table 1C.

Table 1C. Fit of Model to Meter D, First Rangeability Test Data

Model $y = 0.044 + 0.095\,\dot{m}$
Bias at $\dot{m} = 2.5$ kg/s, $y = +0.28\%$
Residual standard deviation = ±0.11%
Number of points = 36

The only significant dependency is with the mass flow rate. The coefficients for $\dot{m}^2$, T, and T^2 were considered and were found not to be statistically significant. The precision based on three times the standard deviation is ±0.33 percent and the bias is +0.28 percent at a flow rate of 2.5 kg/s.

The results of the boundary test of meter D are shown by the scatter plots of figures 7C, 8C, 9C, and 10C. Vapor was formed in the meter at a subcooling of 4 K and below causing the six points of high registration seen in figure 9C. Low subcooling was obtained by reducing the system pressure at a temperature of 90 K. The six high points are seen in figure 8C to occur at 90 K. Since the low subcooling points were the last points taken in the boundary test, the six high points are the highest ordered points of figure 7C. The very high subcooling (near 24 K) points were obtained by applying refrigeration at the subcooler to obtain temperatures near 70 K. Figure 8C shows an increase in registration at this temperature.

The results of the stability tests are shown in figures 11C, 12C, 13C, and 14C. During the 80 hours of this test 870 m^3 (230,000 gallons) of liquid were metered.

The effect of wear may be seen by examining figure 11C. A straight line fitted to these data has a slope of 0.002%/point. This results in an increase of overregistration by 0.26 percent for the 130 data points of the stability test. This meter is unique as it is the only meter tested that showed an increase in registration with an increase in the amount of liquid metered.

The results of the second rangeability test are shown in figures 15C, 16C, 17C, and 18C. The fit of the mathematical model to these data is given in table 2C.

Table 2C. Fit of Model to Meter D, Second Rangeability Test Data

Model $y = -1.26 + 0.022\ T$
Bias at $T = 80$ K, $y = +0.50\%$
Residual standard deviation $= \pm 0.16\%$
Number of points = 29

The coefficients for T^2, $\dot{m}$, and $\dot{m}^2$ were considered but were found not to be statistically significant. The only significant dependency was found with temperature. The precision based on three times the standard deviation is ±0.48 percent and the bias is +0.50 percent at a temperature of 80 K.

The pressure drop data are shown in figure 19C.

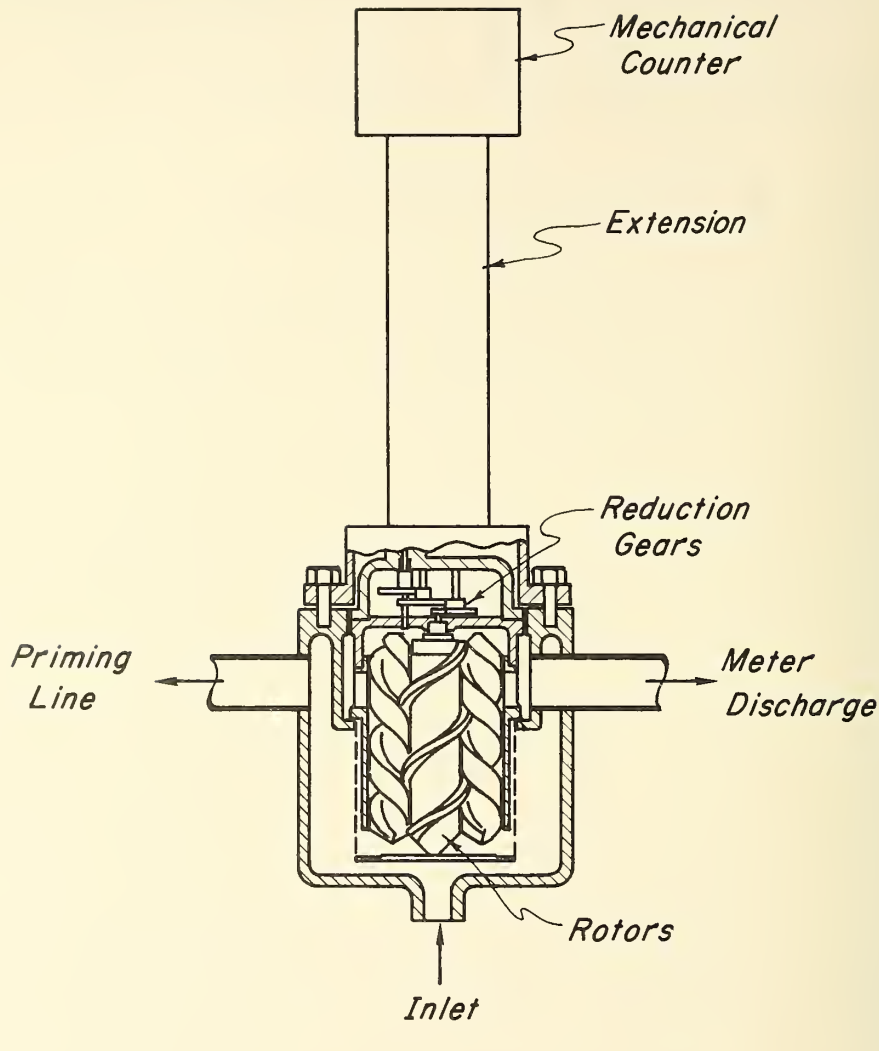

Figure 1C. Screw Impeller Meter with a Mechanical Counter.

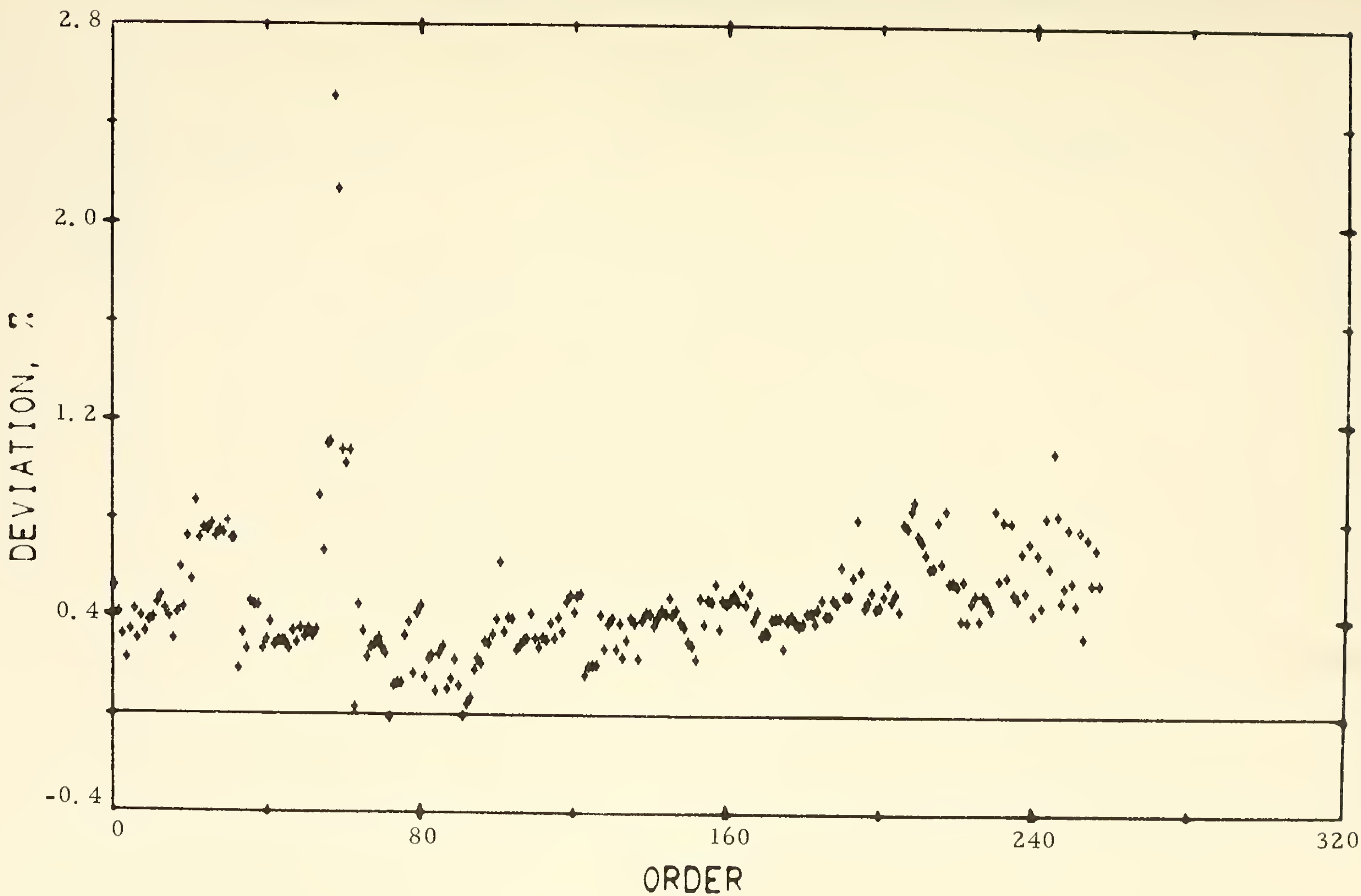

Figure 2C. Meter D, Performance Data from all Tests.

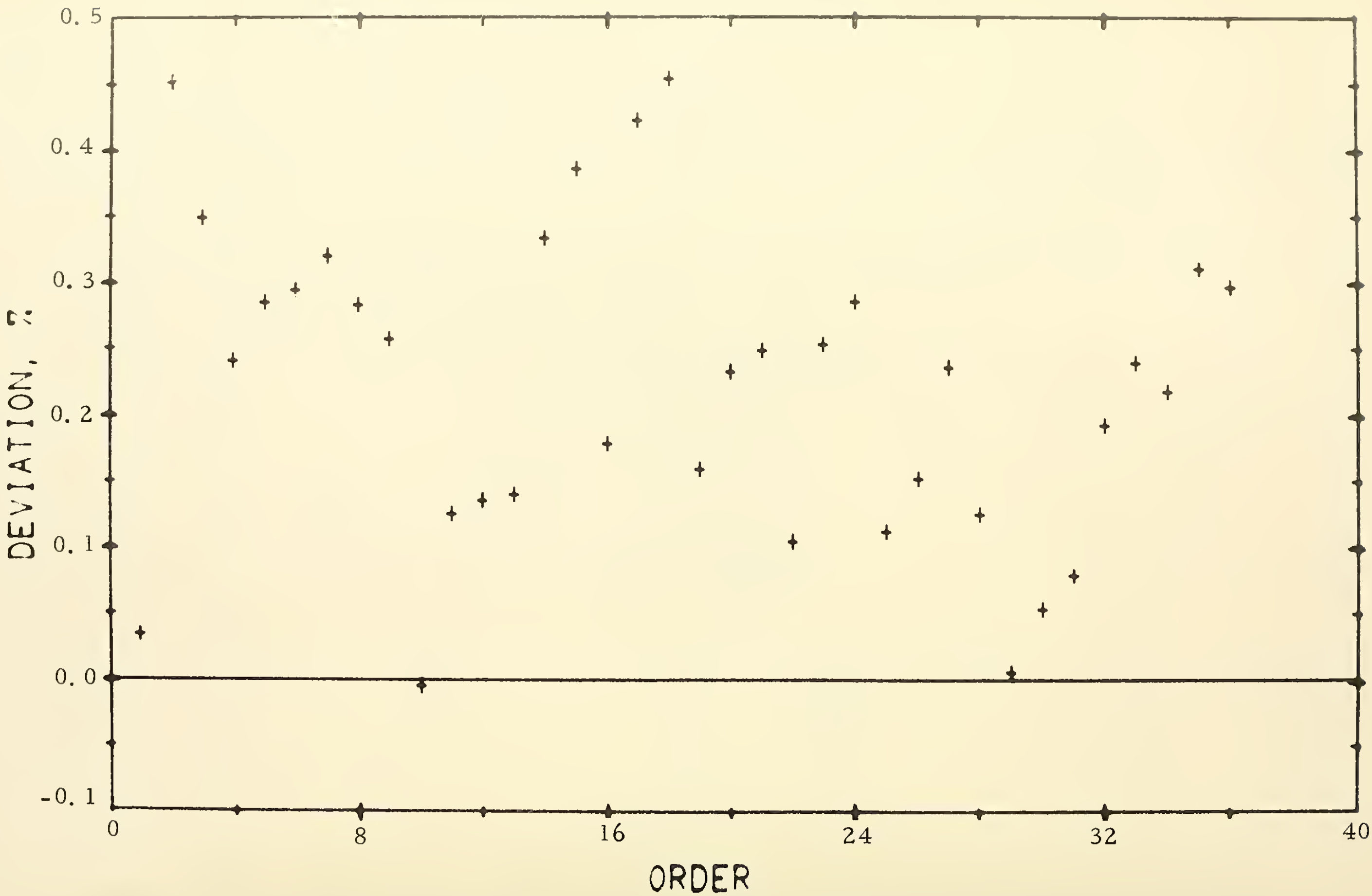

Figure 3C. Meter D, Performance vs. Order, First Rangeability Test.

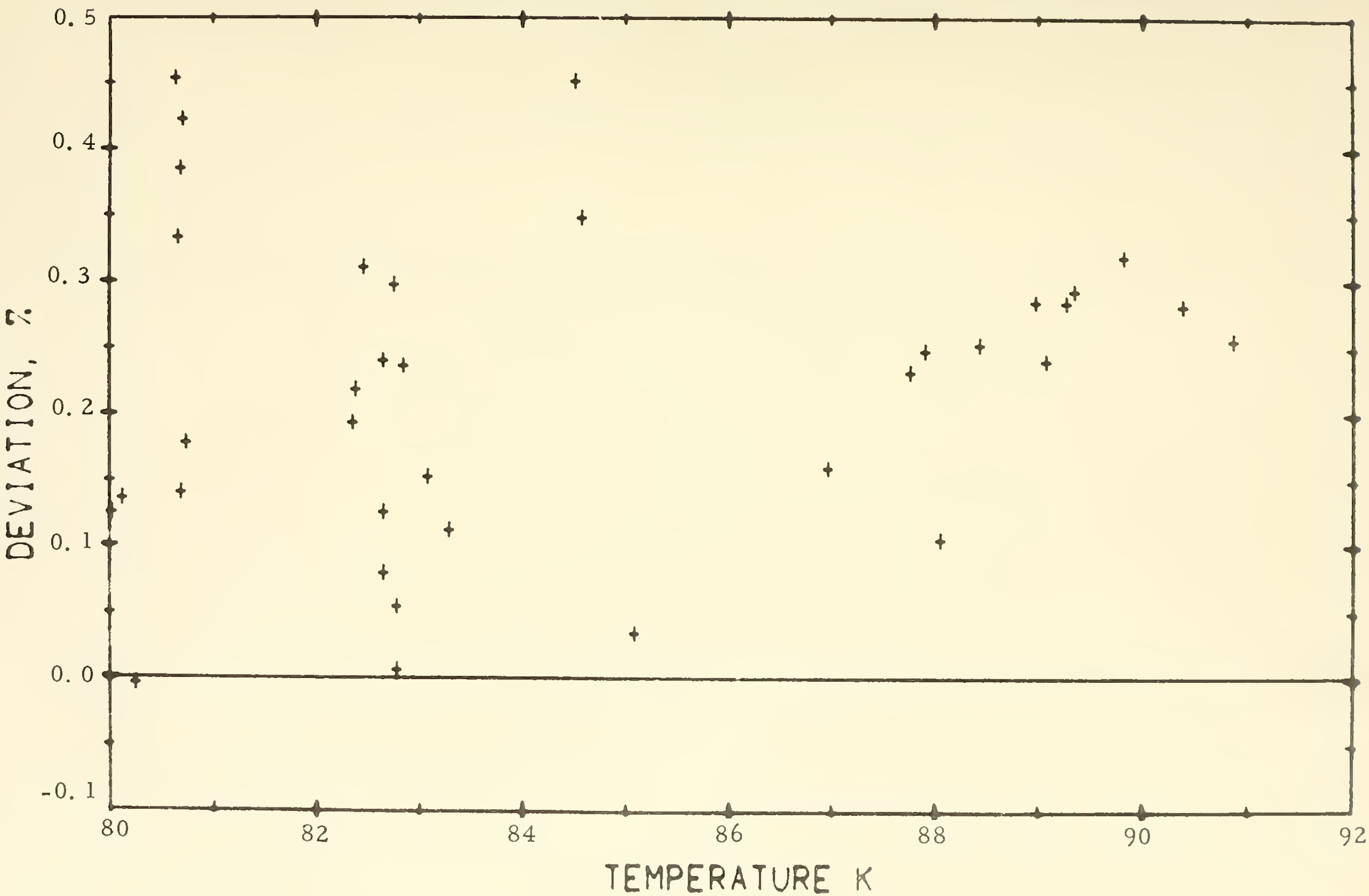

Figure 4C. Meter D, Performance vs. Temperature, First Rangeability Test.

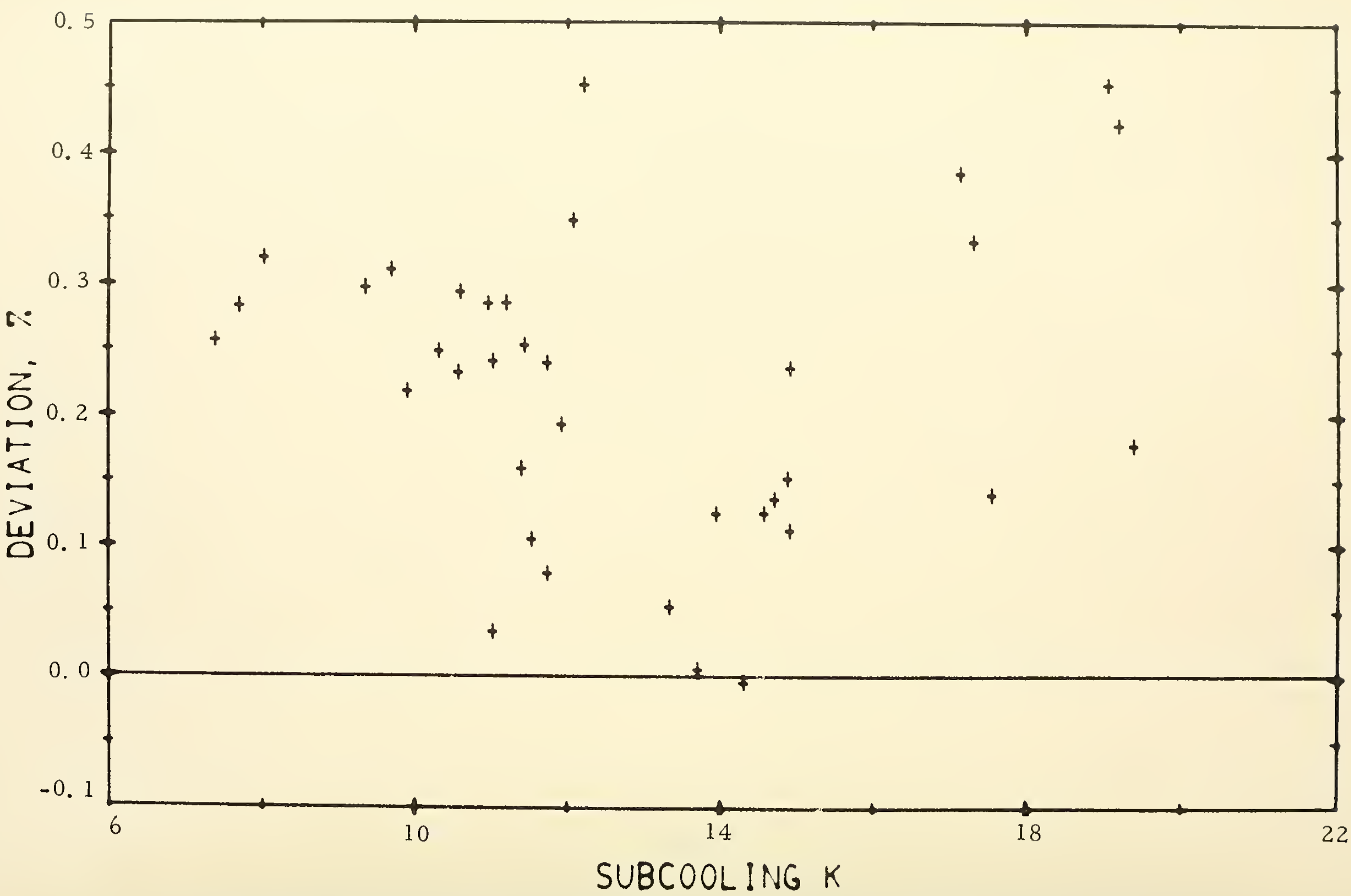

Figure 5C. Meter D, Performance vs. Subcooling, First Rangeability Test.

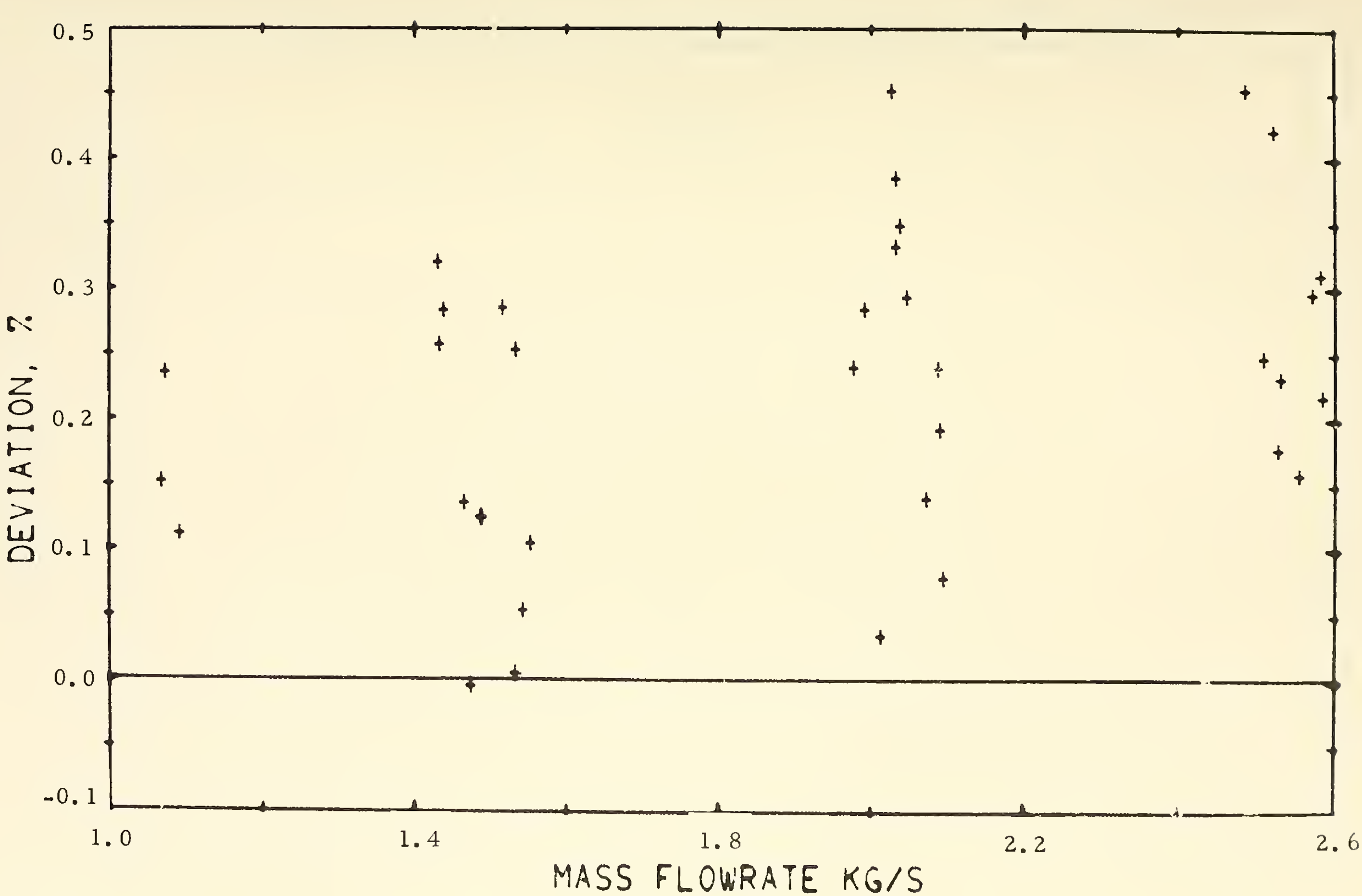

Figure 6C. Meter D, Performance vs. Mass Flow Rate, First Rangeability Test.

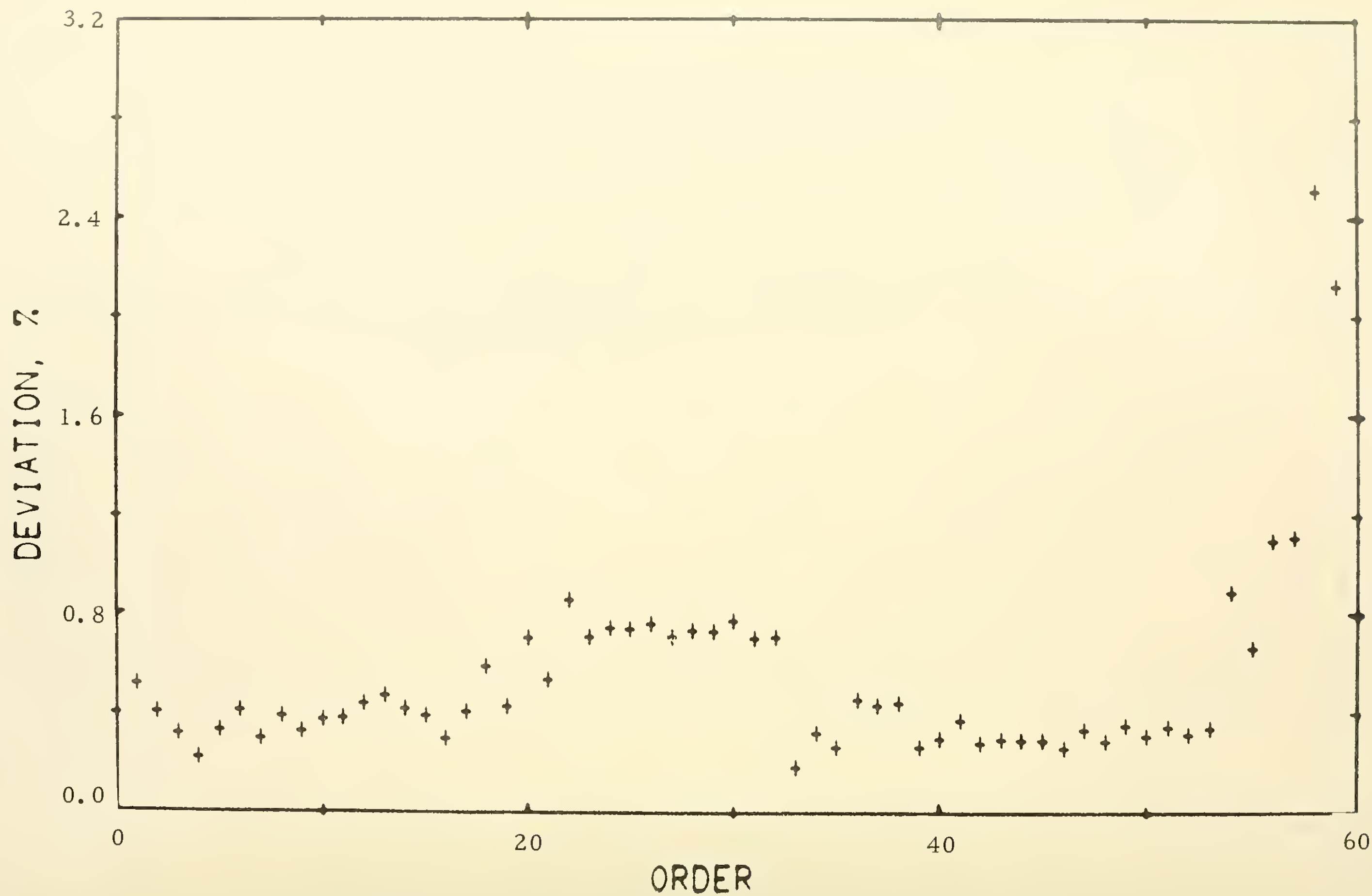

Figure 7C. Meter D, Performance vs. Order, Boundary Test.

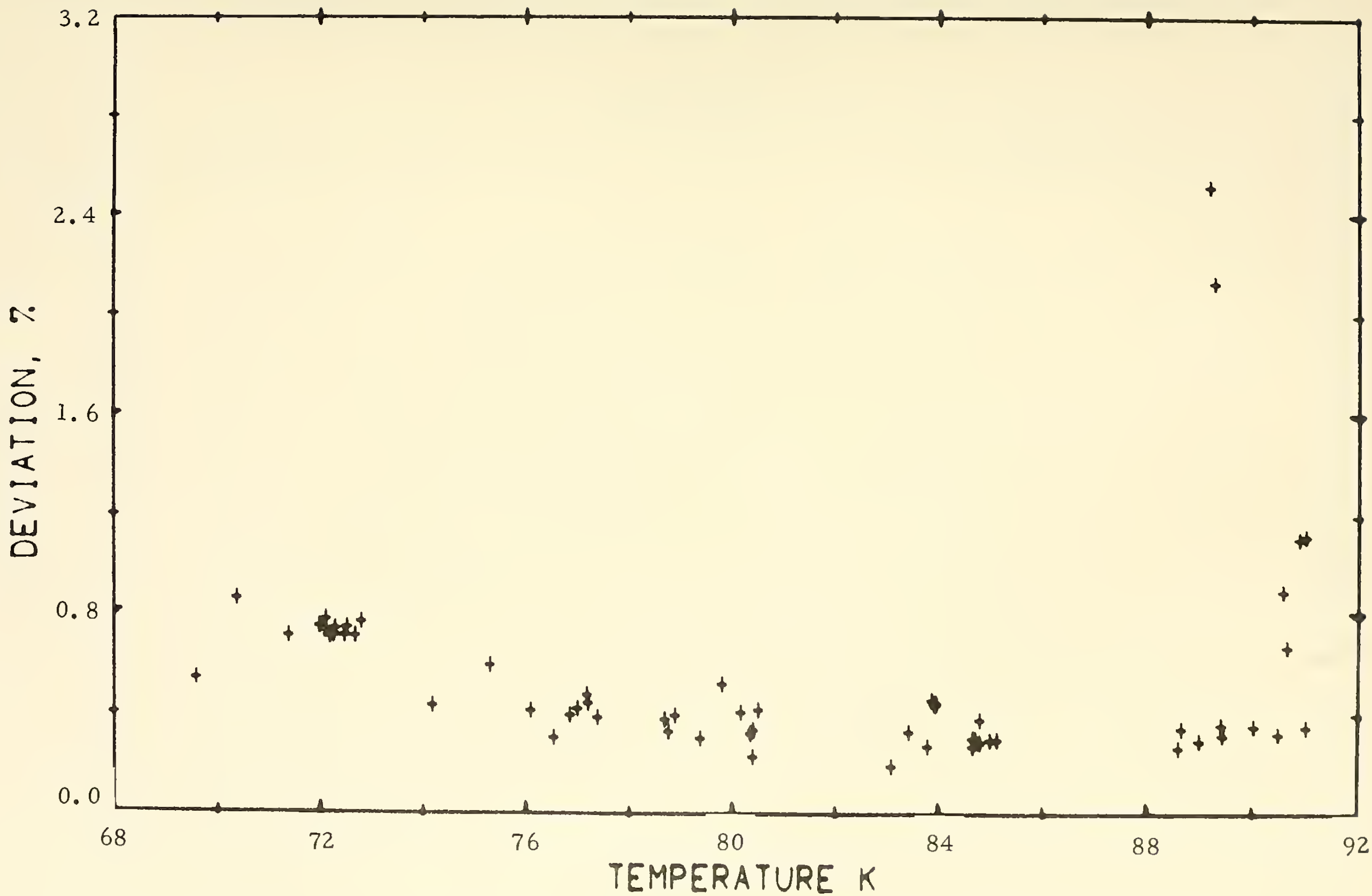

Figure 8C. Meter D, Performance vs. Temperature, Boundary Test.

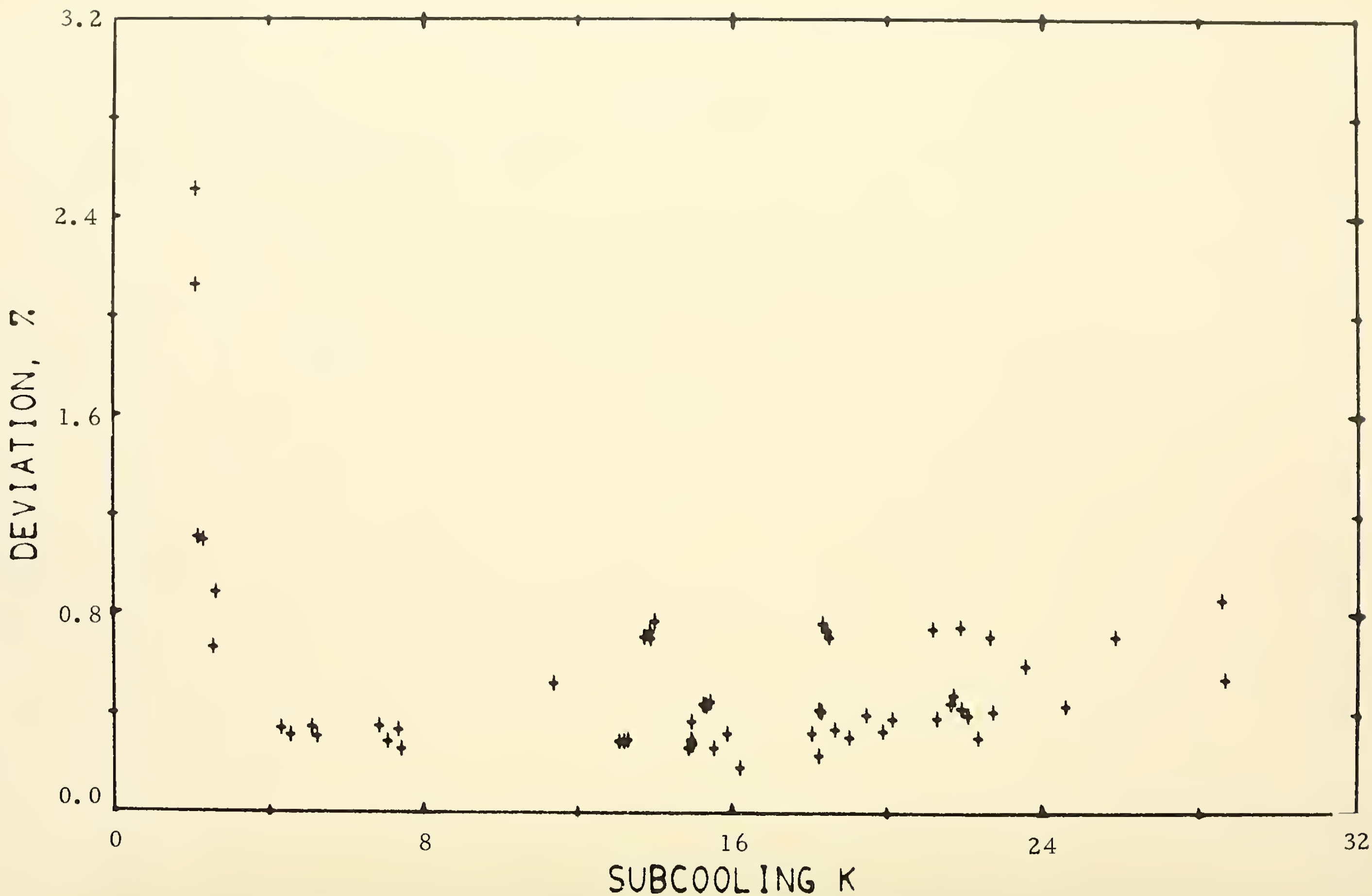

Figure 9C. Meter D, Performance vs. Subcooling, Boundary Test.

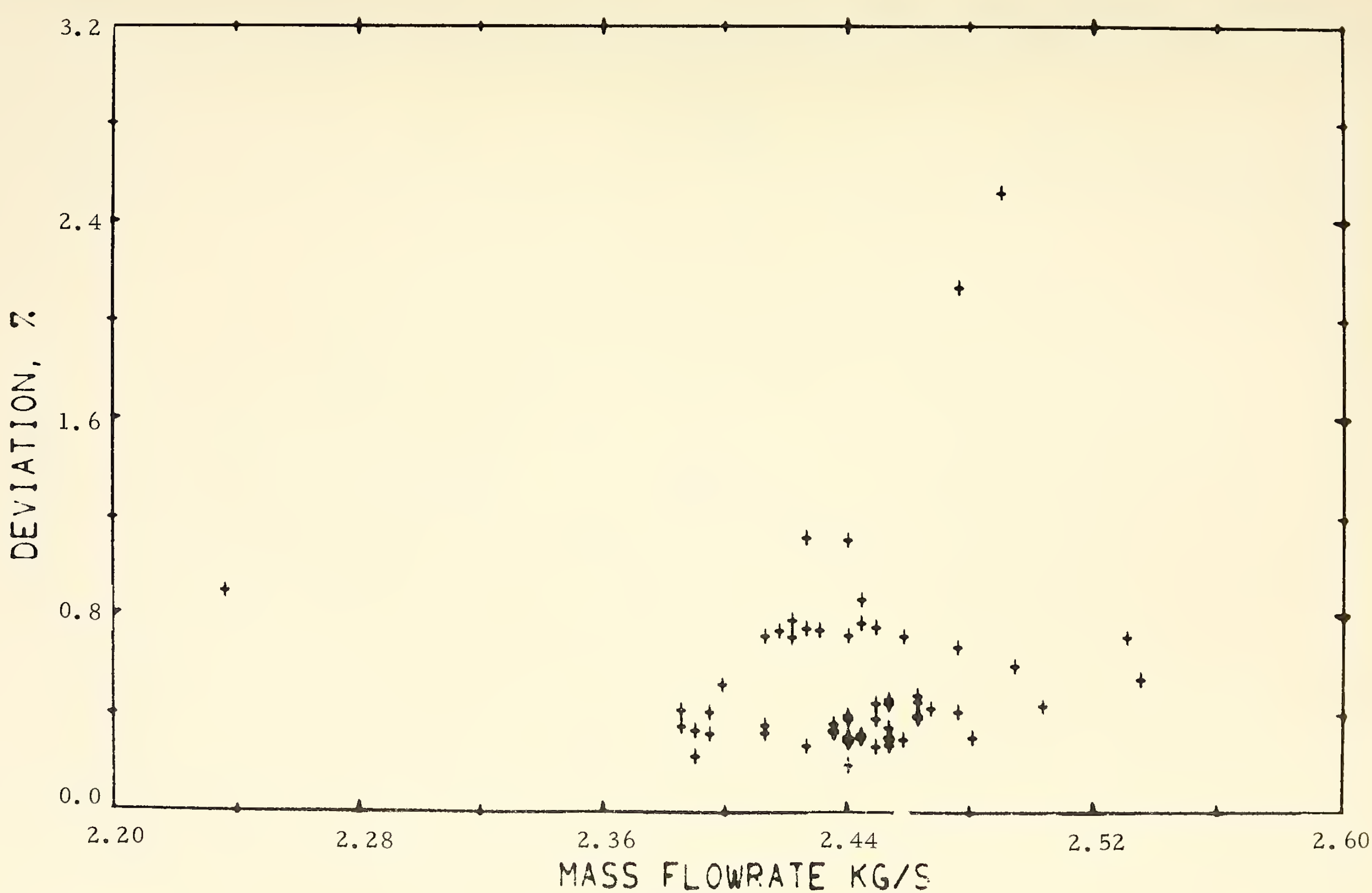

Figure 10C. Meter D, Performance vs. Mass Flow Rate, Boundary Test.

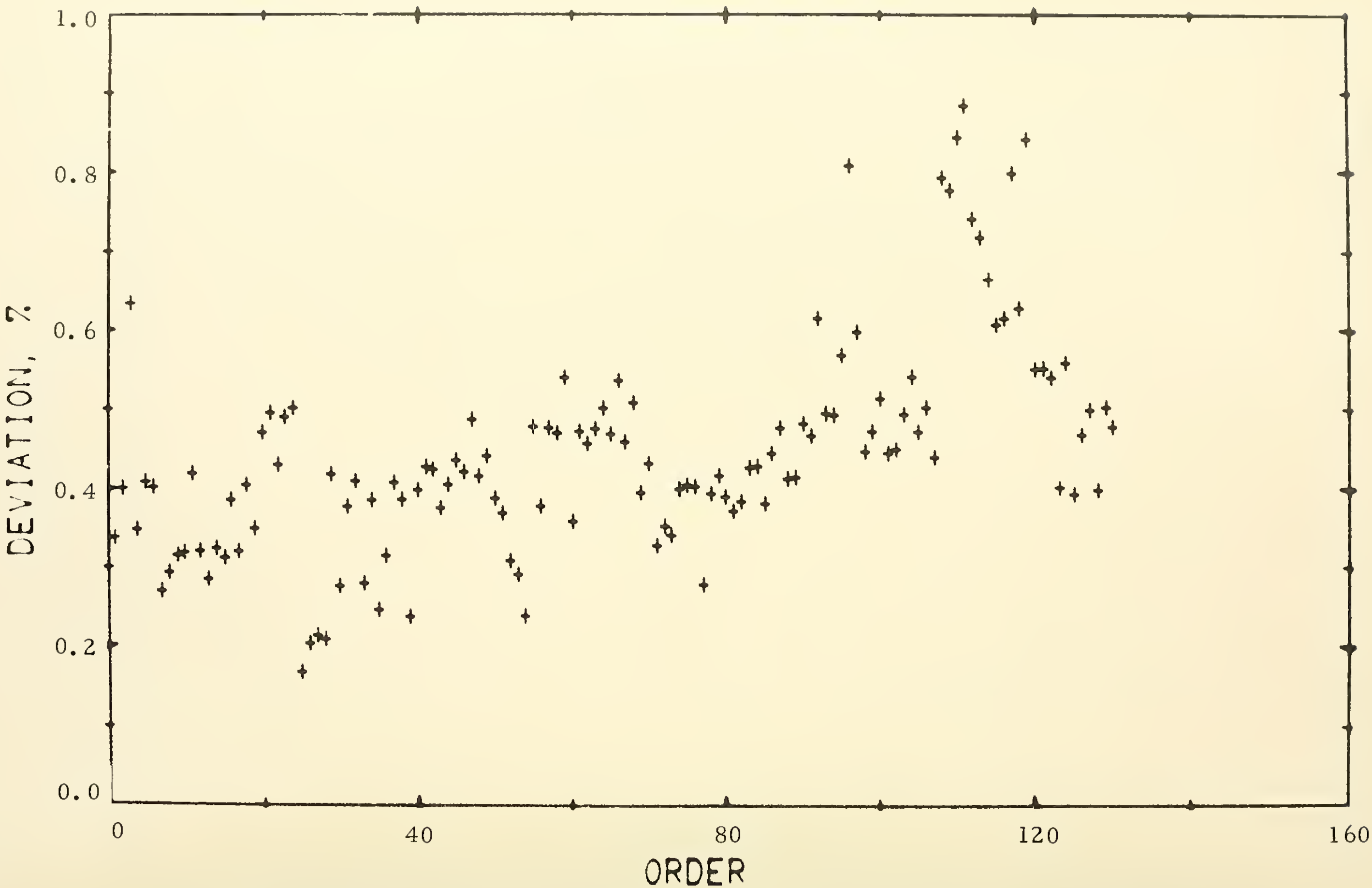

Figure 11C Meter D, Performance vs. Order, Stability Test.

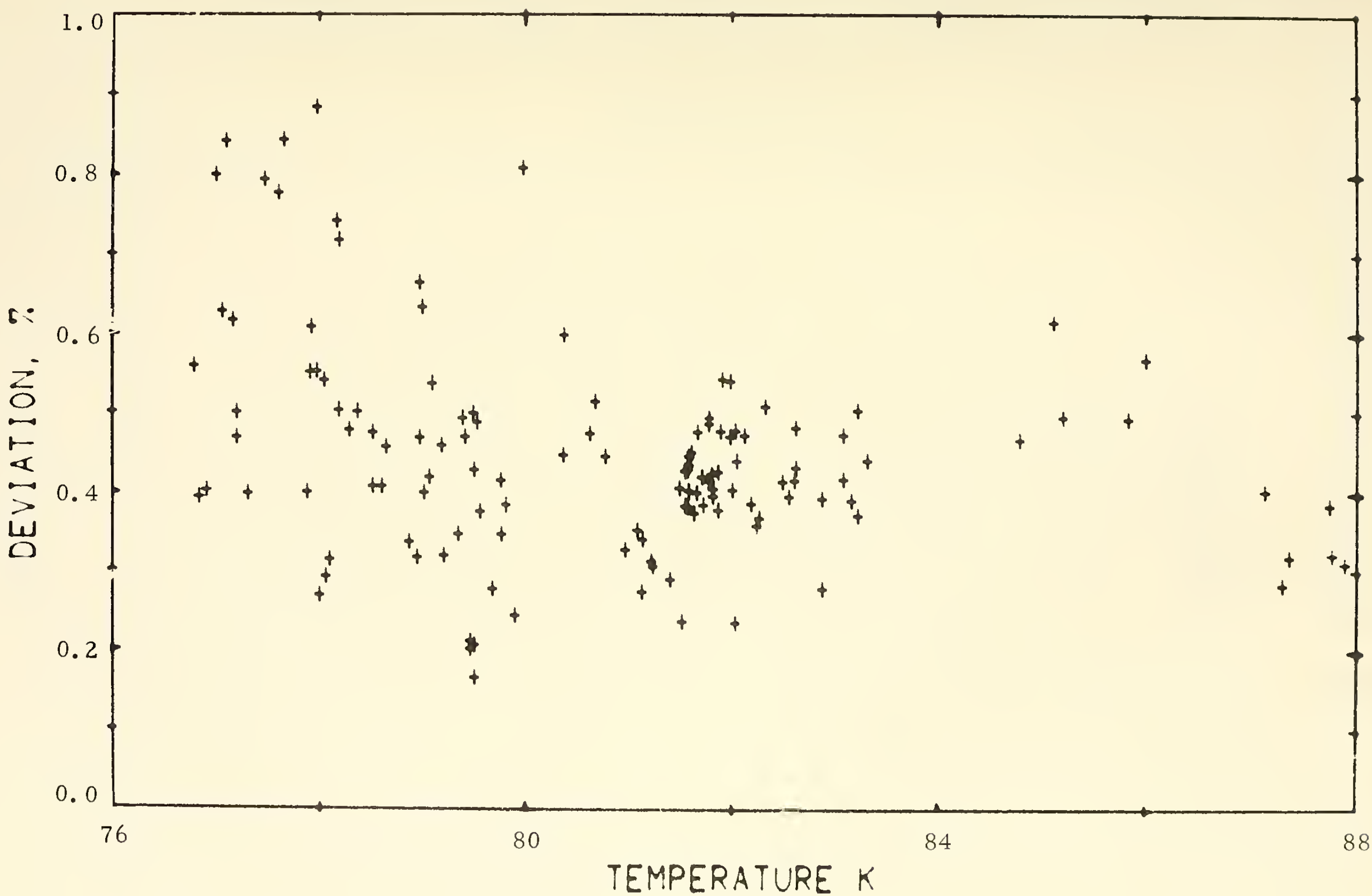

Figure 12C. Meter D, Performance vs. Temperature, Stability Test.

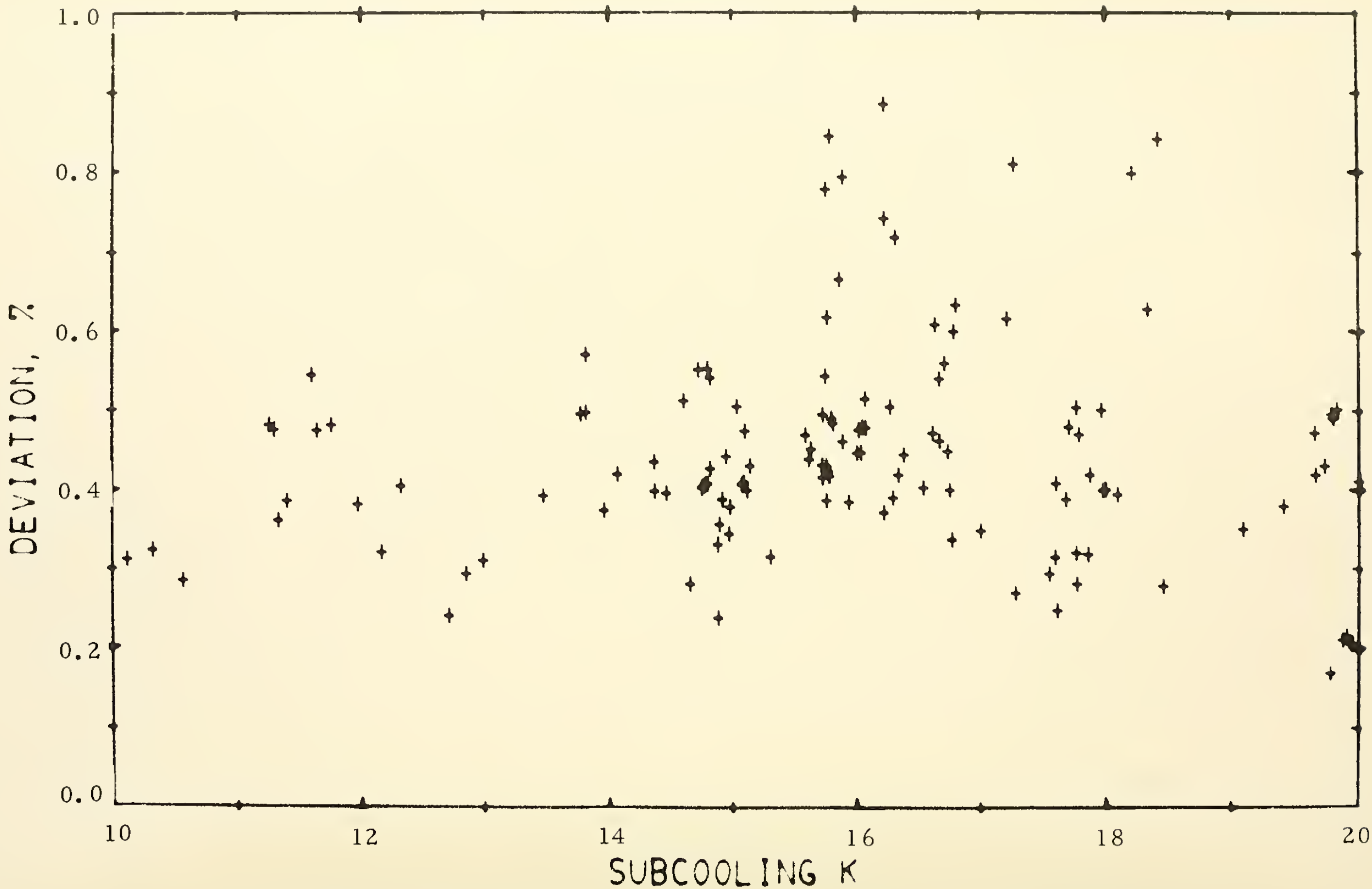

Figure 13C. Meter D, Performance vs. Subcooling, Stability Test.

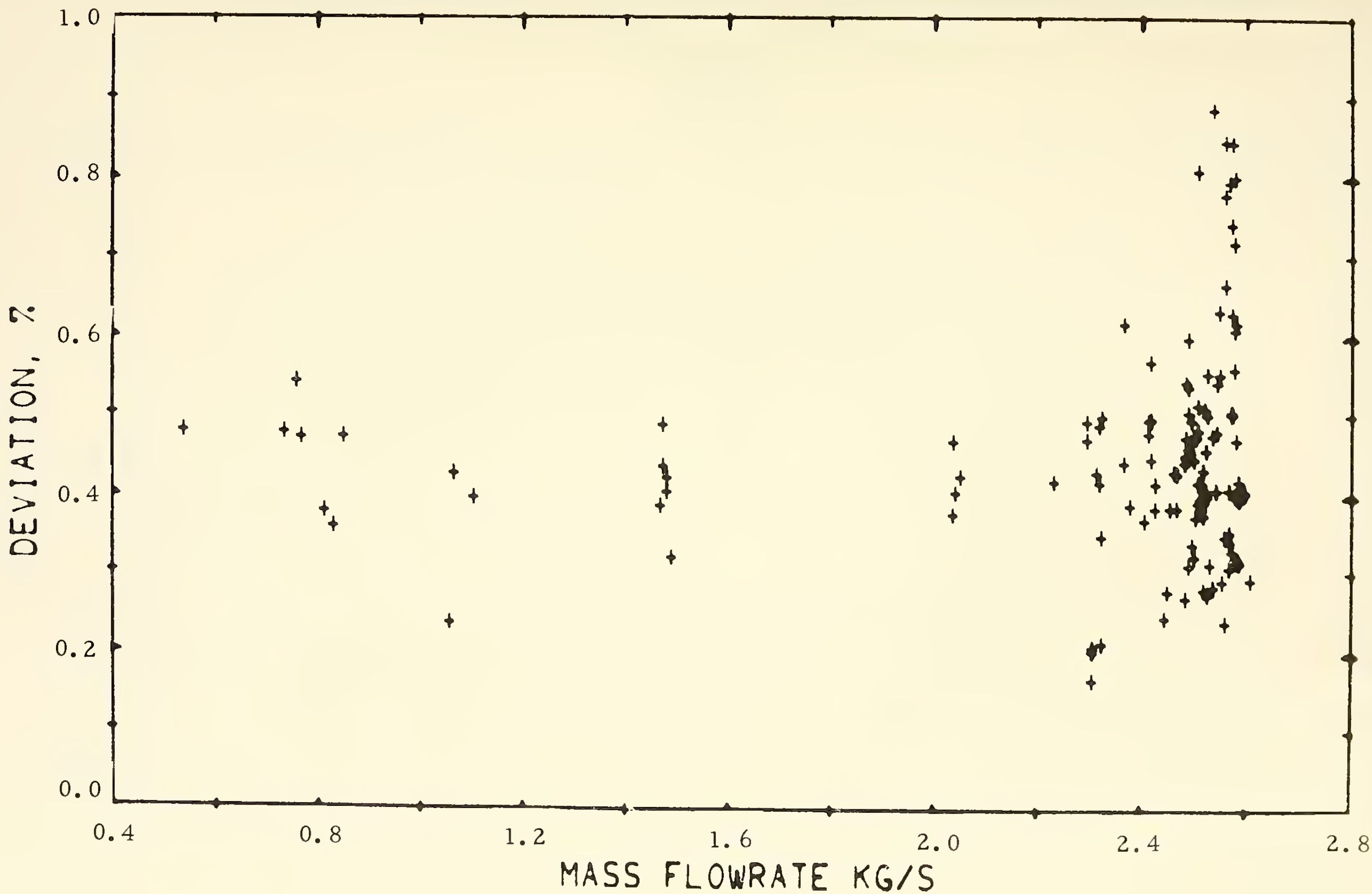

Figure 14C. Meter D, Performance vs. Mass Flow Rate, Stability Test.

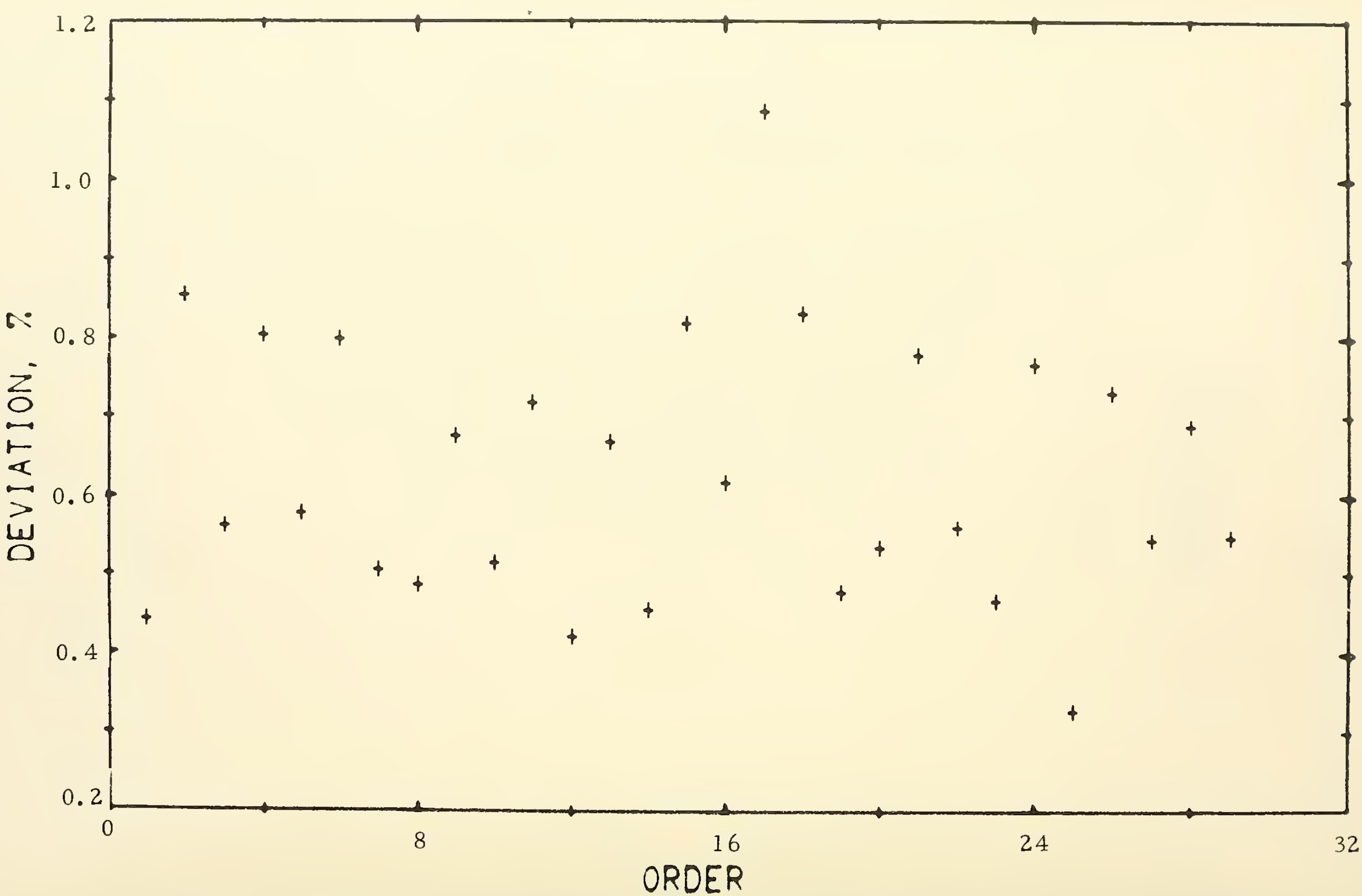

Figure 15C. Meter D, Performance vs. Order, Second Rangeability Test.

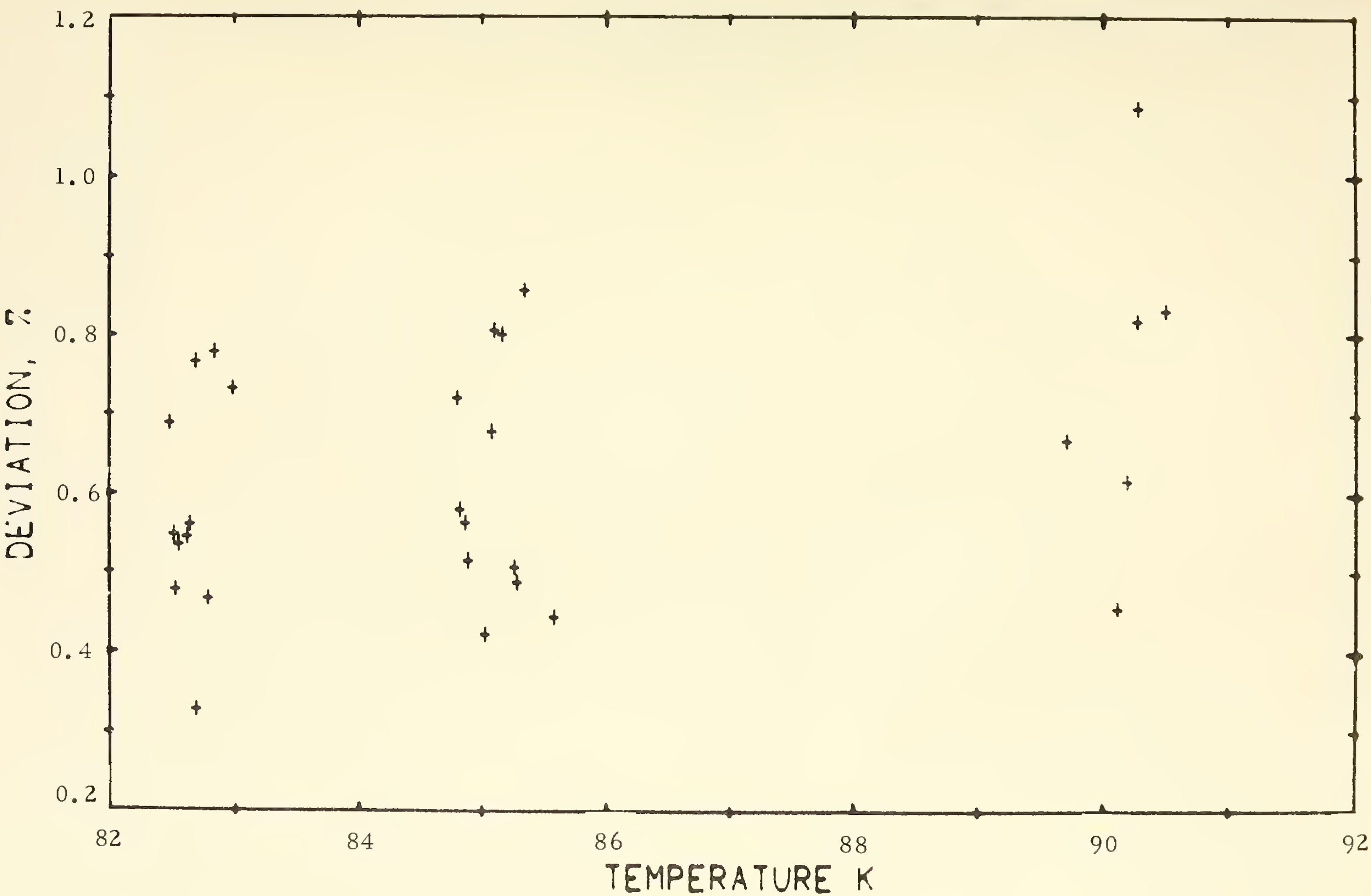

Figure 16C. Meter D, Performance vs. Temperature, Second Rangeability Test.

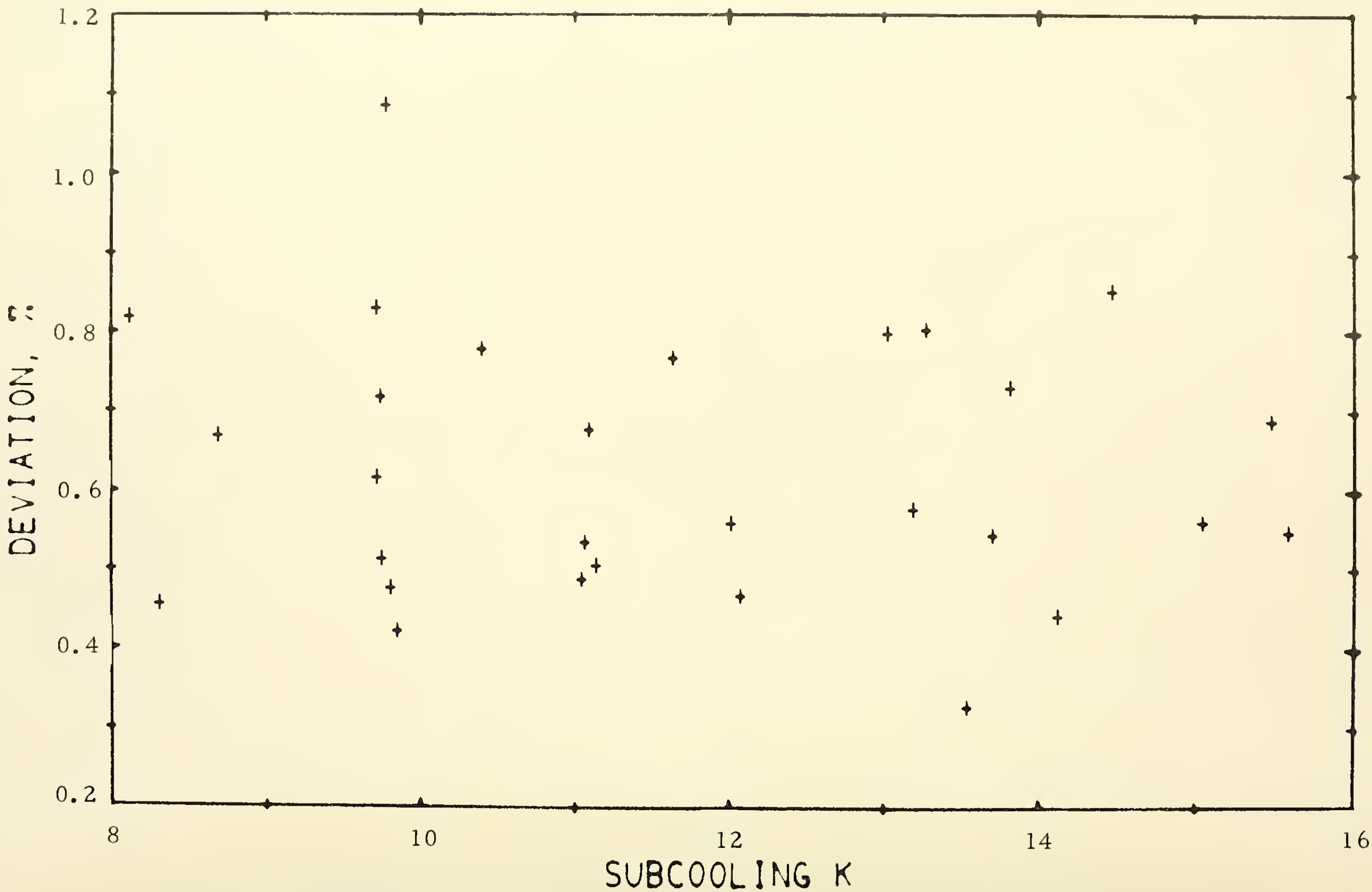

Figure 17C. Meter D, Performance vs. Subcooling, Second Rangeability Test.

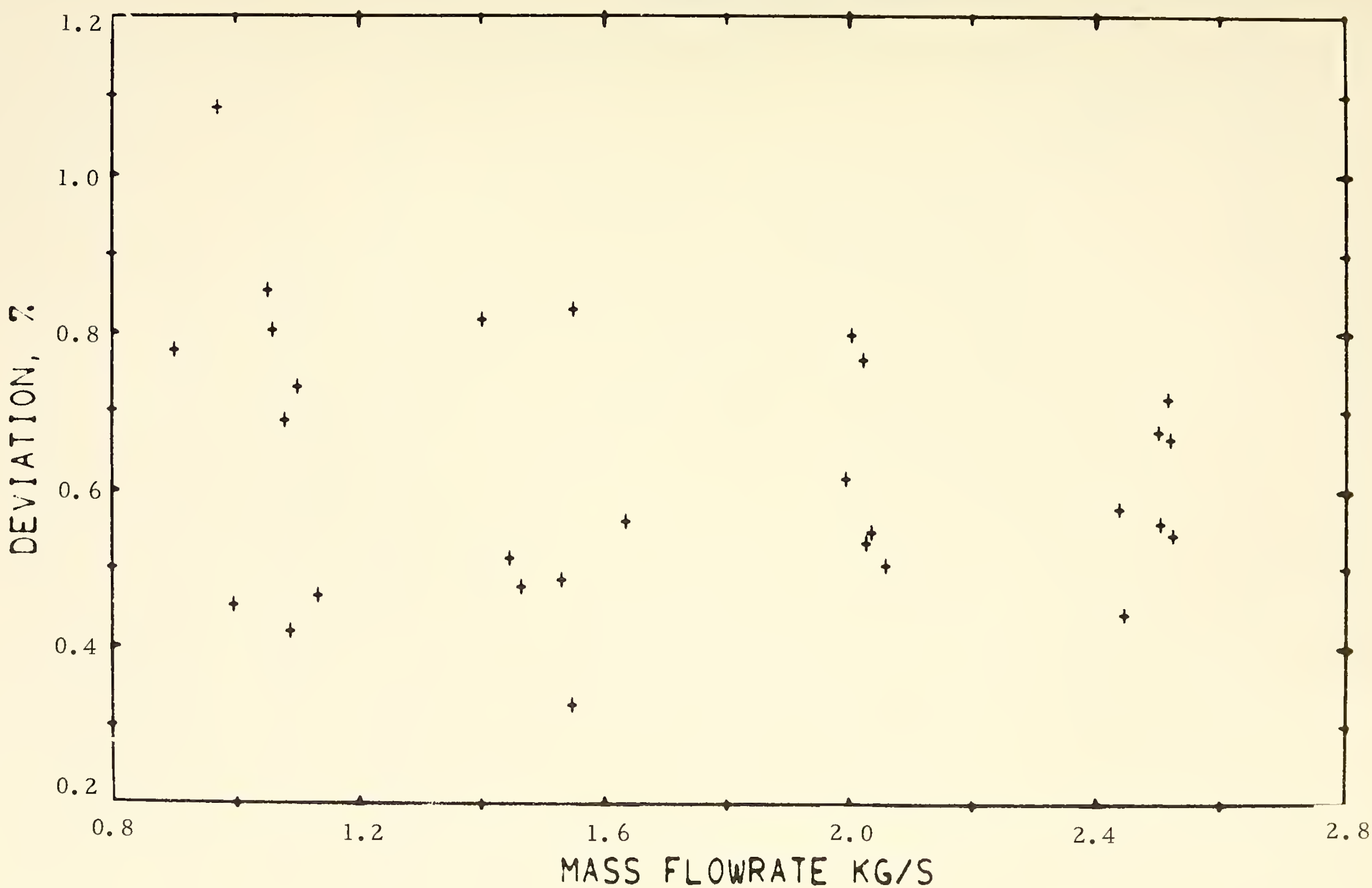

Figure 18C. Meter D, Performance vs. Mass Flow Rate, Second Rangeability Test.

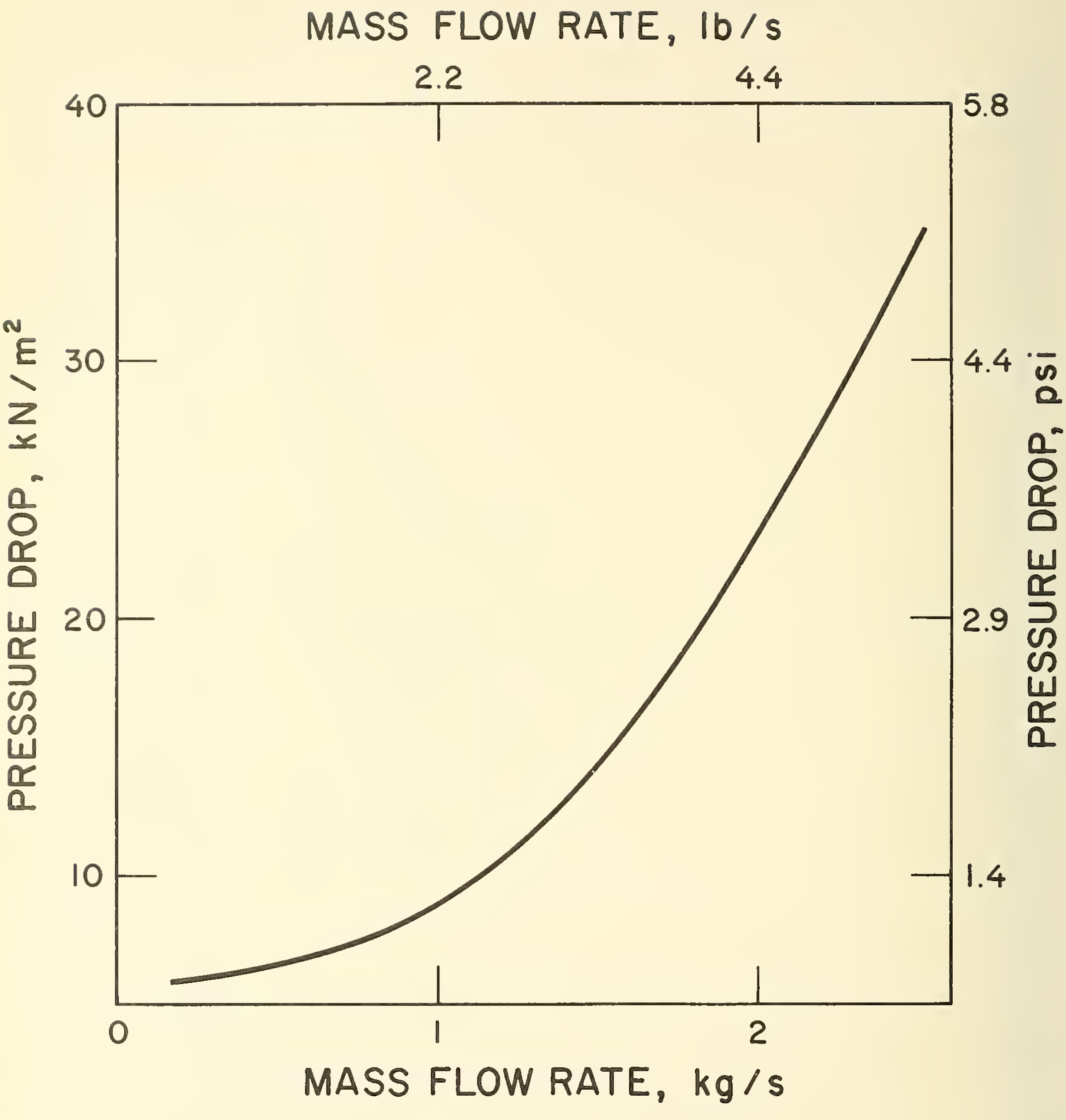

Figure 19C. Meter D Pressure Drop.

APPENDIX D. Performance of a Rotating Vane Meter with a Mechanical Counter (Meter L)

This meter is illustrated in figure 1D. Priming was accomplished by utilizing two 1/4-inch pipe case drains. Liquid is admitted to the inlet and is first taken out the priming line to cool the meter to operating temperature. After priming, liquid passes through the rotor assembly turning the vanes that are geared to the register. A pulser is attached to the register that consists of a single rotating magnet and a latching reed switch. The magnet rotates on an axis perpendicular to the reed causing the reed to move between two contact points.

The meter suppliers specifications are:

fluid -- liquid oxygen

maximum flow rate -- 0.0063 m^3/s (100 gpm)

minimum flow rate -- 0.0013 m^3/s (20 gpm)

maximum pressure -- 2.068 MN/m^2 (300 psia)

material -- aluminum

register -- mechanical register in 0.0003785 m^3 (0.1 gal)
electrical register in 0.003785 m^3/pulse (1 gal/pulse).

This type of meter is available with a vapor eliminator and an automatic temperature compensator. Neither of these features were evaluated.

This meter registers the swept volume of the positive displacement element in U. S. gallons (0.003785 m^3). No meter design density information was specified; therefore, the volumetric meter factor was 0.003785 m^3/pulse (1 gallon/pulse). Two meters (G and L) of this type were evaluated. Meter G failed by the rotor coming in contact with the case after 113.5 m^3 (30,000 gallons) of liquid were metered. A replacement meter body was obtained and the register from meter G was attached by the factory representative. The register stack had two pulsers and a plastic thermal isolator in addition to the register.

Since the meter registration is in volume units, no density corrections are required to obtain the results shown in this report.

Preliminary tests of this meter (L) indicated that the meter was malfunctioning. The results of this test are given in figure 2D where a flow rate dependency of 7 percent is indicated over the flow range. The factory representative inspected the meter and determined that drag was occurring in the register stack. The register drive shaft was found to be rubbing on the plastic spacer. The plastic spacer was relieved to eliminate this interference and the meter retested. A flow rate dependency of 11 percent is again shown in figure 3D.

The entire mechanical register was then removed and a NBS magnetic pickup attached directly to the main output shaft. The results showed a precision of ±0.42 percent without a flow rate dependency. It is believed that the strong flow rate dependency previously seen was caused by the torque loading imposed on the meter vanes by the register. These data are not further reported.

An attempt was made to obtain a meter configuration that is representative of the meter of this type now in service. The lower pulser and the plastic isolator were removed and the register reassembled on the meter body. A gear change was made that gives the rotating vanes twice the mechanical advantage on the register as in the previous configuration. All further testing was done in the configuration shown in the assembled drawing of figure 1D. Modifications were made by the factory representative.

Data taken for meter L for all tests are shown in figure 4D. The first 49 points were taken at a temperature near 81 K and a pressure near 0.45 MN/m^2 (65 psia) with only the flow rate being varied. Data taken after point 49 are for the representative meter after adjustment by the factory representative.

The results of the first rangeability test of meter L are shown in figures 5D, 6D, 7D, and 8D. The fit of the mathematical model to these data is given in table 1D.

Table 1D. Fit of Model to Meter L, First Rangeability Test Data

Model $y = 2.91 - 0.029\,T + 0.49\,\dot{m} - 0.08\,\dot{m}^2$
Bias at $T = 80$ K and $\dot{m} = 5$ kg/s, $y = +1.04\%$
Residual standard deviation = ±0.23%
Number of points = 62

Significant dependency exists with temperature, mass flow rate, and the square of mass flow rate. The coefficient for T^2 was considered and found not to be statistically significant. The precision based on three times the standard deviation is ±0.69 percent and the bias is ±1.04 percent at a temperature of 80 K and a flow rate of 5 kg/s.

The boundary test results are shown in figures 9D, 10D, 11D, and 12D. Examination of figure 11D shows no subcooling dependency. The flow rate was lowered to reduce the pressure drop across the meter and to allow the liquid at the meter inlet to more closely approach the saturated condition. Cavitation in the meter was not observed at the sight glass at the meter outlet nor is it evident in the data.

The results of the stability test are shown in figures 13D, 14D, 15D, and 16D. The order dependency of figure 13D shows a very strong wear effect. A linear fit was made to these data resulting in a slope of -0.044%/point. Since there are 126 points, the change in meter registration is -5.5 percent for 1333 m^3 (352,219 gallons) of liquid over an 80 hour test period.

The results of the second rangeability test of meter L are shown in figures 17D, 18D, 19D, and 20D. The fit of the mathematical model to these data is given in table 2D.

Table 2D. Fit of Model to Meter L, Second Rangeability Test Data

Model $y = -420.7 + 9.99\,T - 0.0604\,T^2 + 0.65\,\dot{m}$
Bias at $T = 80$ K and $\dot{m} = 5$ kg/s, $y = -4.8\%$
Residual standard deviation = ±0.69%
Number of points = 24

Significant dependencies were found with temperature, the square of temperature, and the mass flow rate. The coefficient for $\dot{m}^2$ was considered but was found not to be statistically significant. The precision based on three times the standard deviation is ±2.1 percent and the bias is -4.8 percent at a temperature of 80 K and a flow rate of 5 kg/s.

The pressure drop data are shown in figure 21D. The initial data taken showed a pressure drop of 34.5 kN/m^2 (5 psi) at the maximum rated flow rate. However, as wear increased the pressure drop increased to about twice this value.

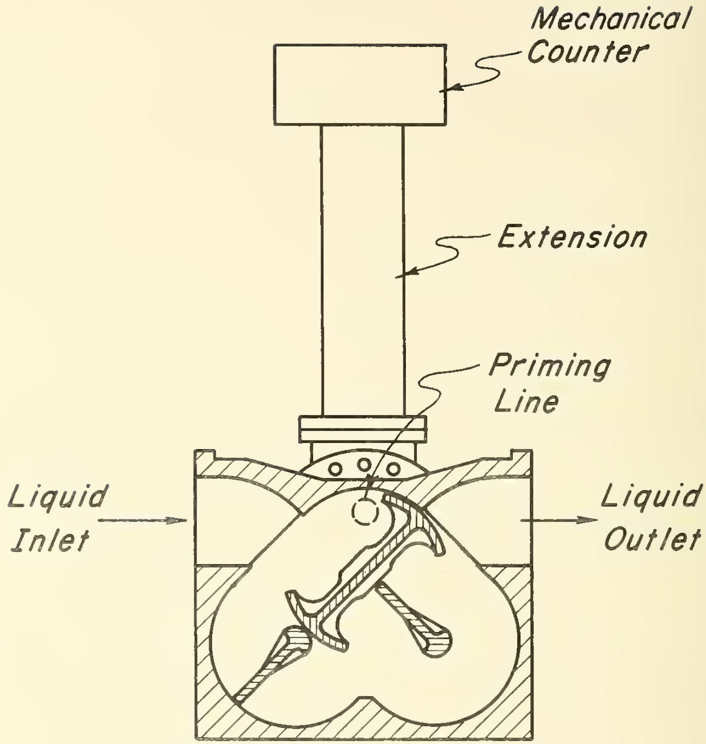

Figure 1D. Rotating Vane Meter.

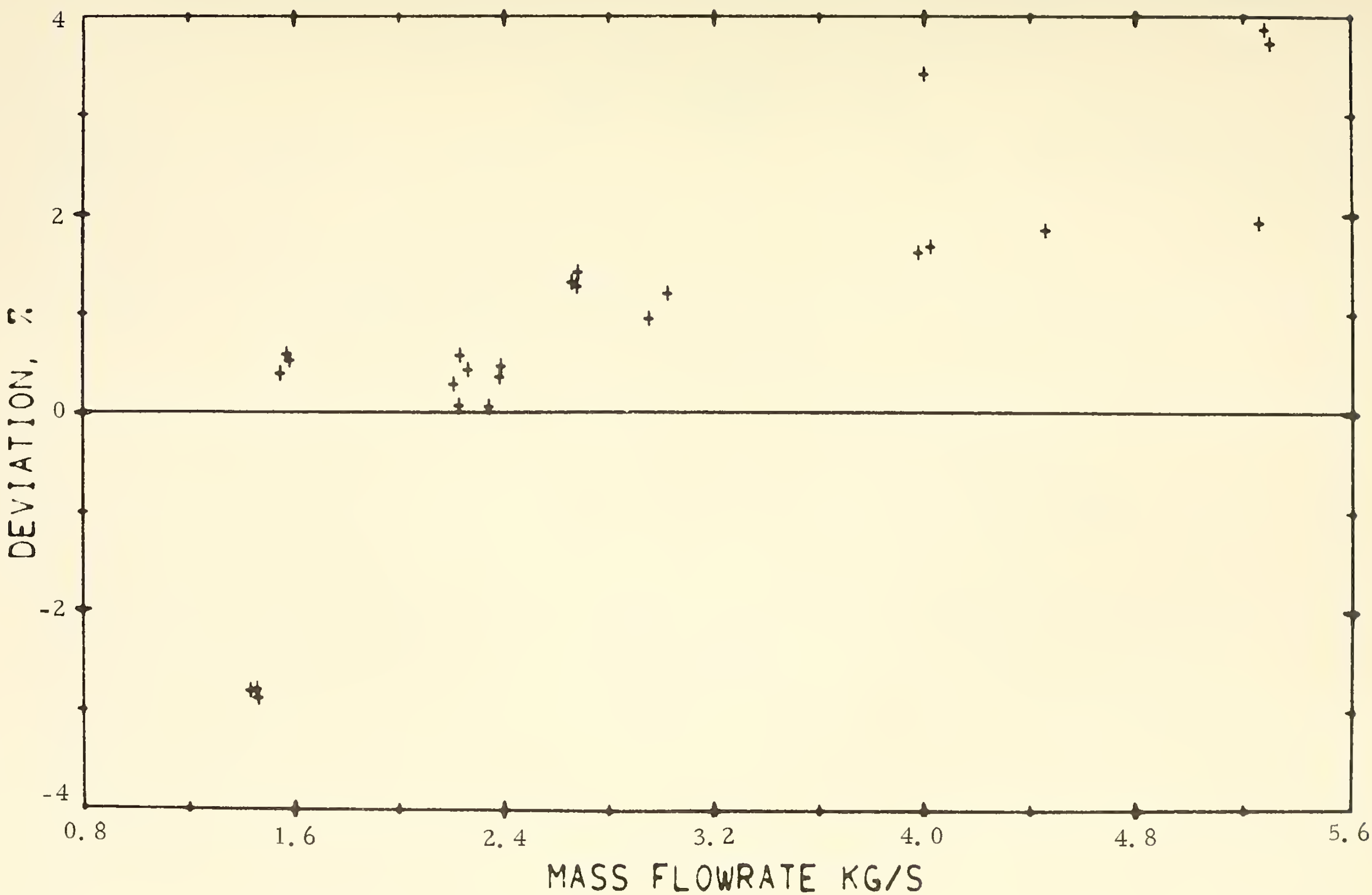

Figure 2D. Meter L, First Flow Range Test.

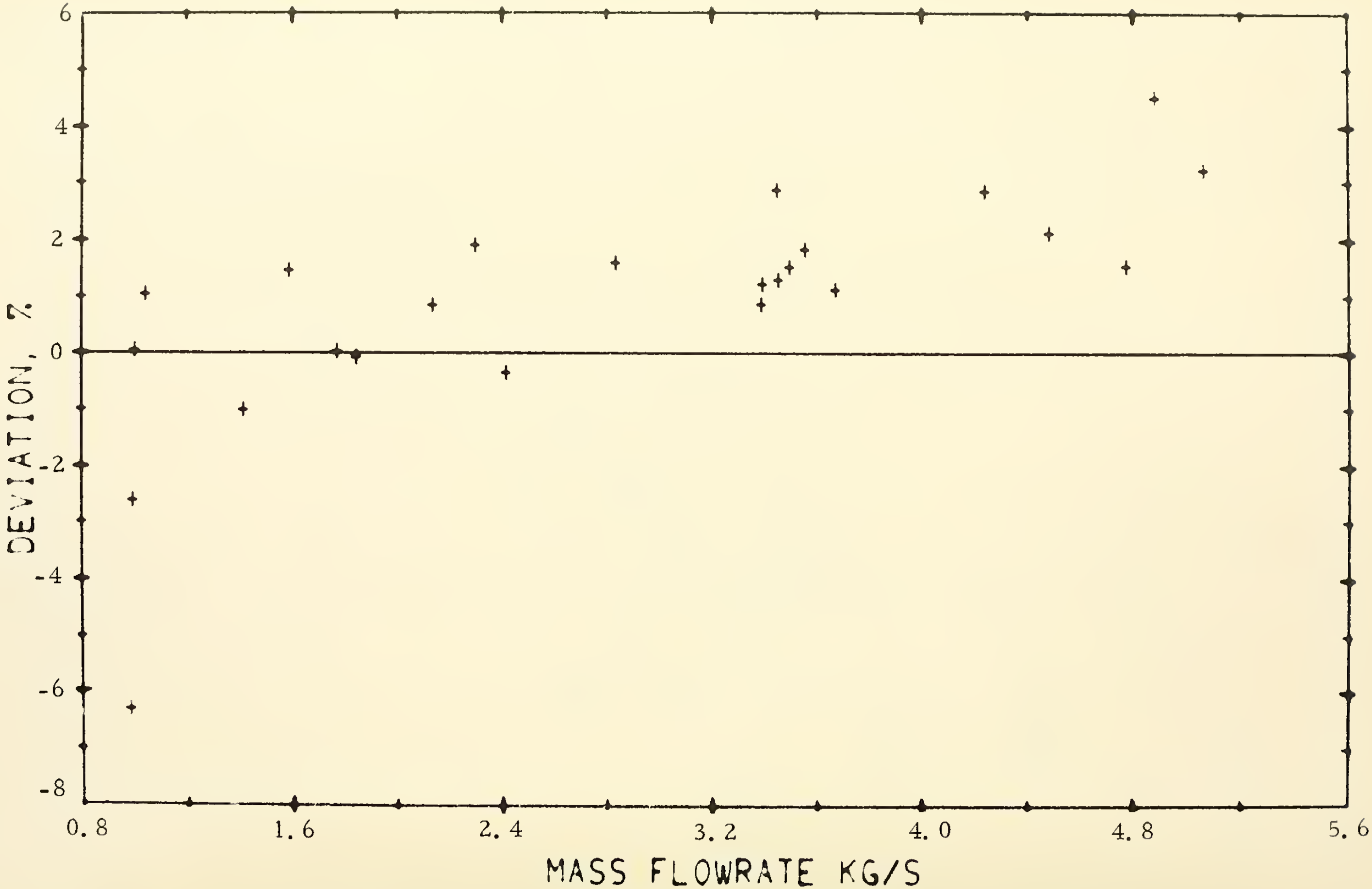

Figure 3D. Meter L, Second Flow Range Test.

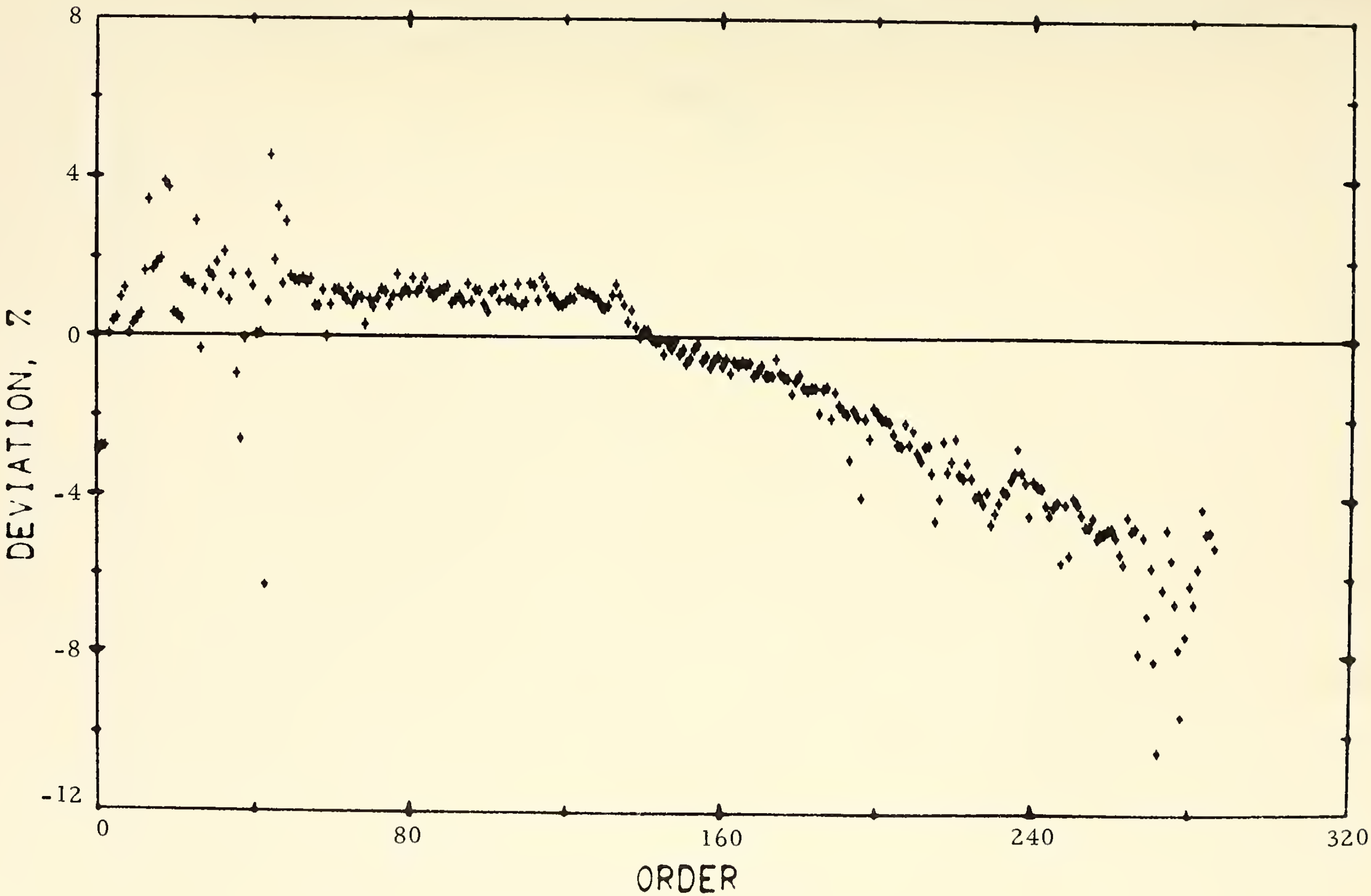

Figure 4D. Meter L, Performance Data from all Tests.

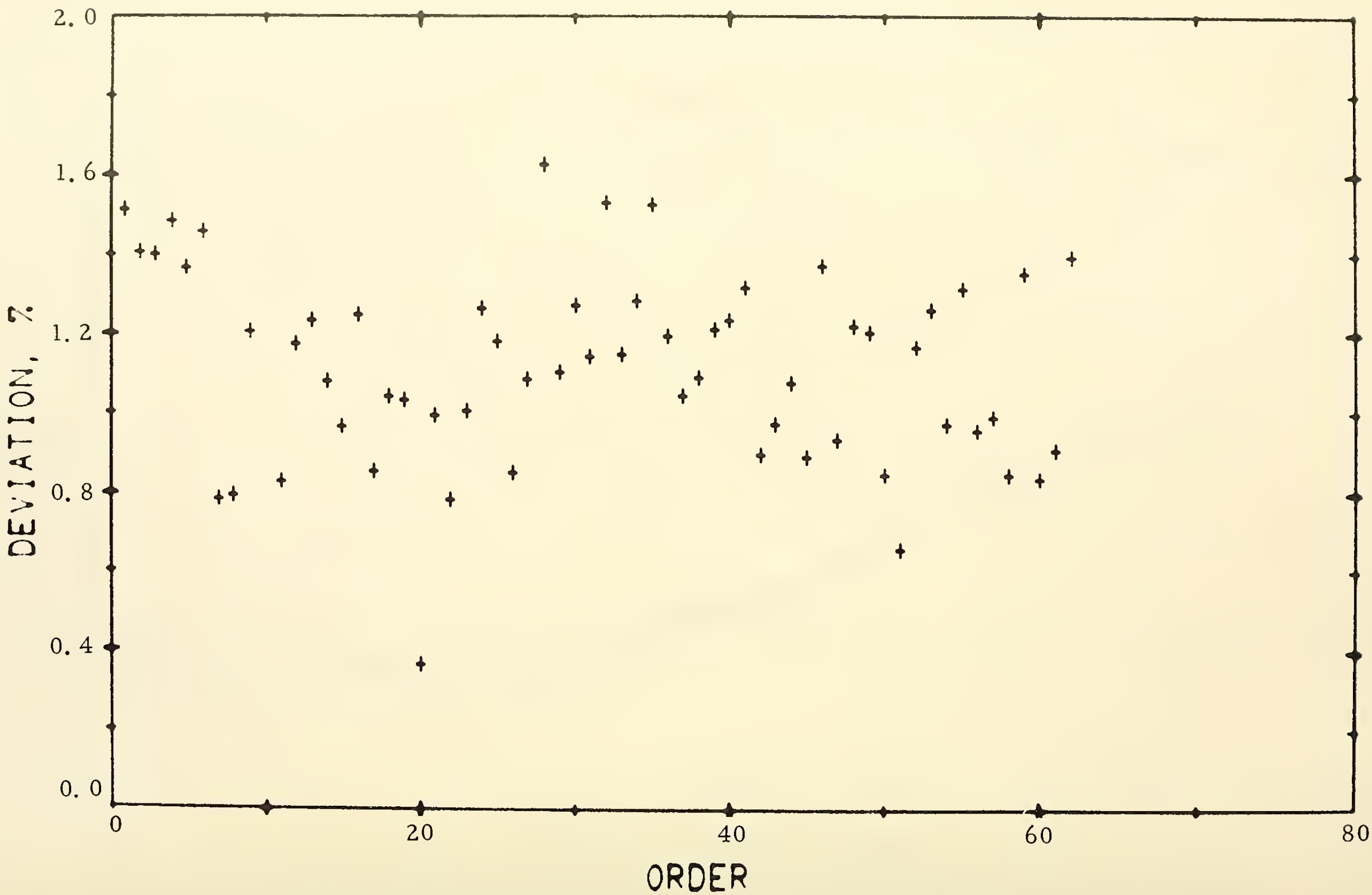

Figure 5D. Meter L, Performance vs. Order, First Rangeability Test.

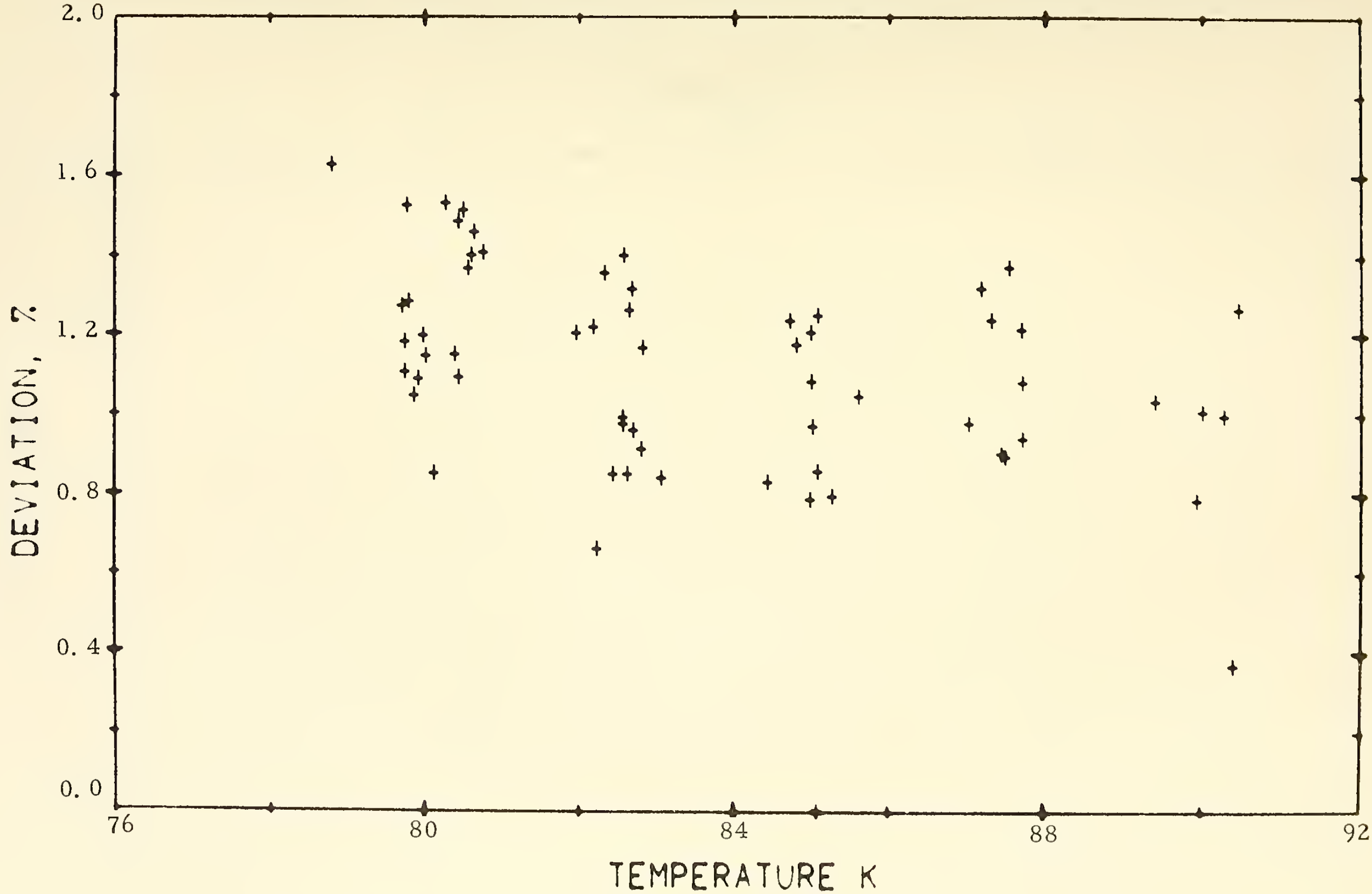

Figure 6D. Meter L, Performance vs. Temperature, First Rangeability Test.

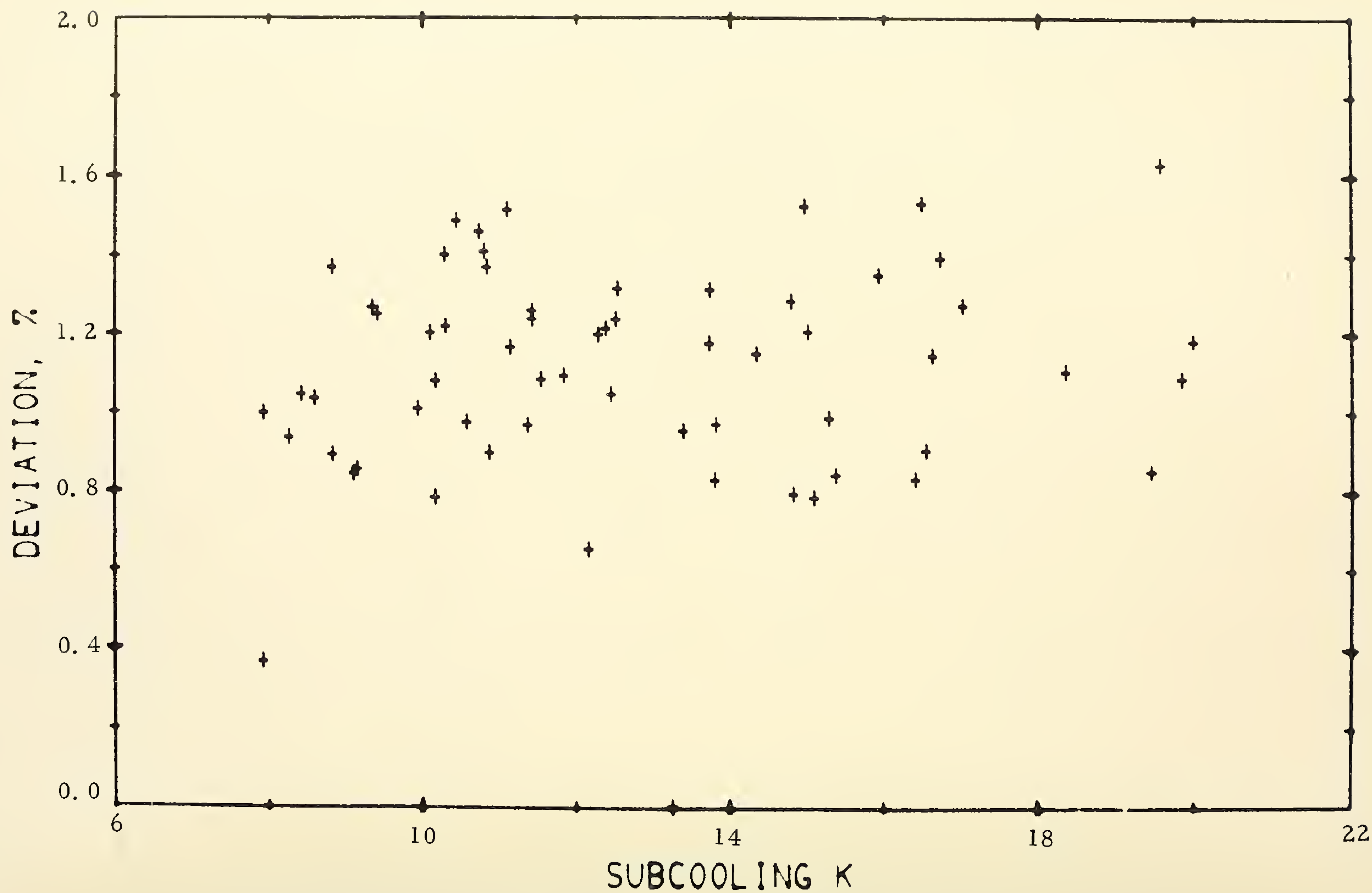

Figure 7D. Meter L, Performance vs. Subcooling, First Rangeability Test.

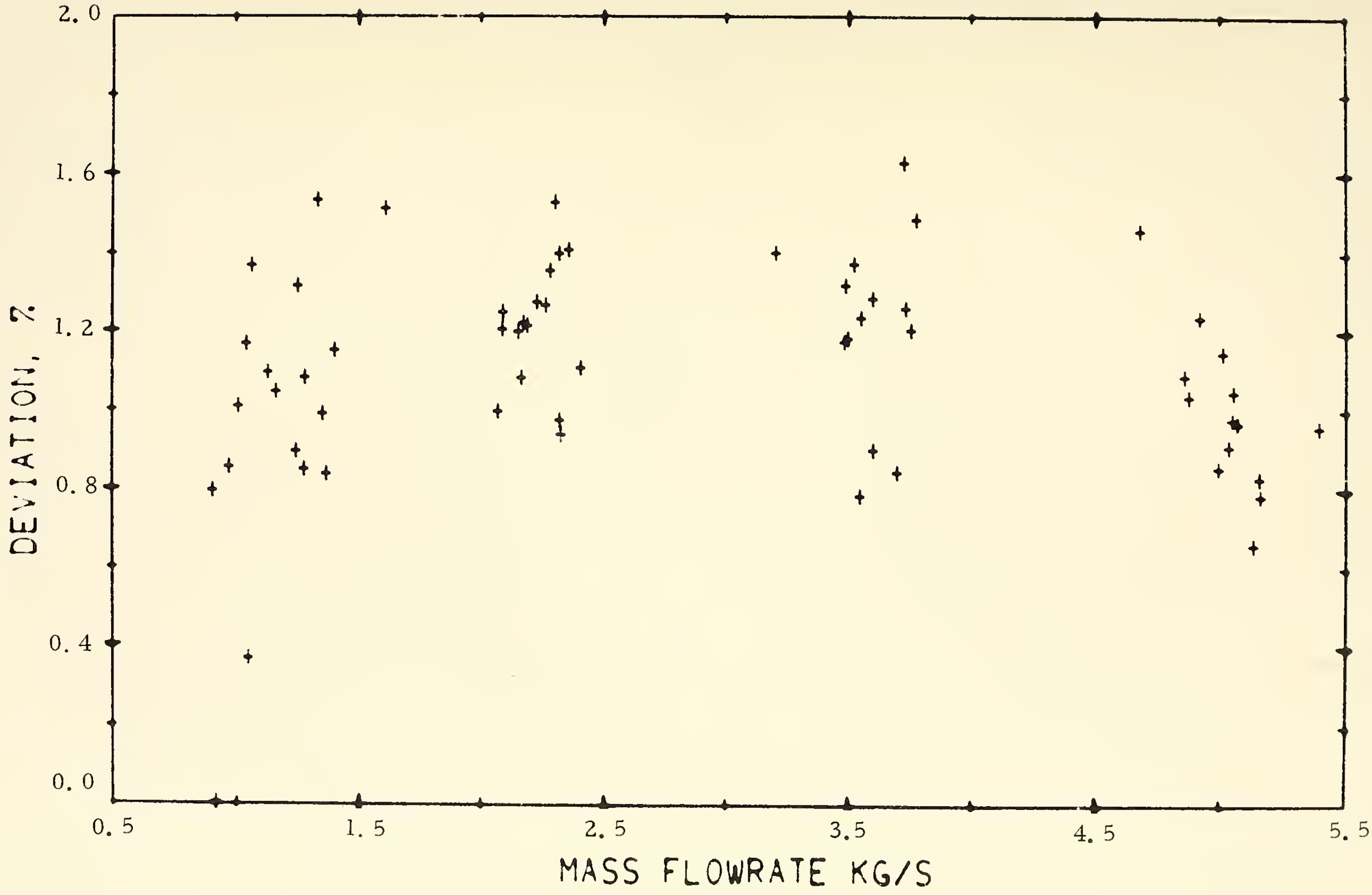

Figure 8D. Meter L, Performance vs. Mass Flow Rate, First Rangeability Test.

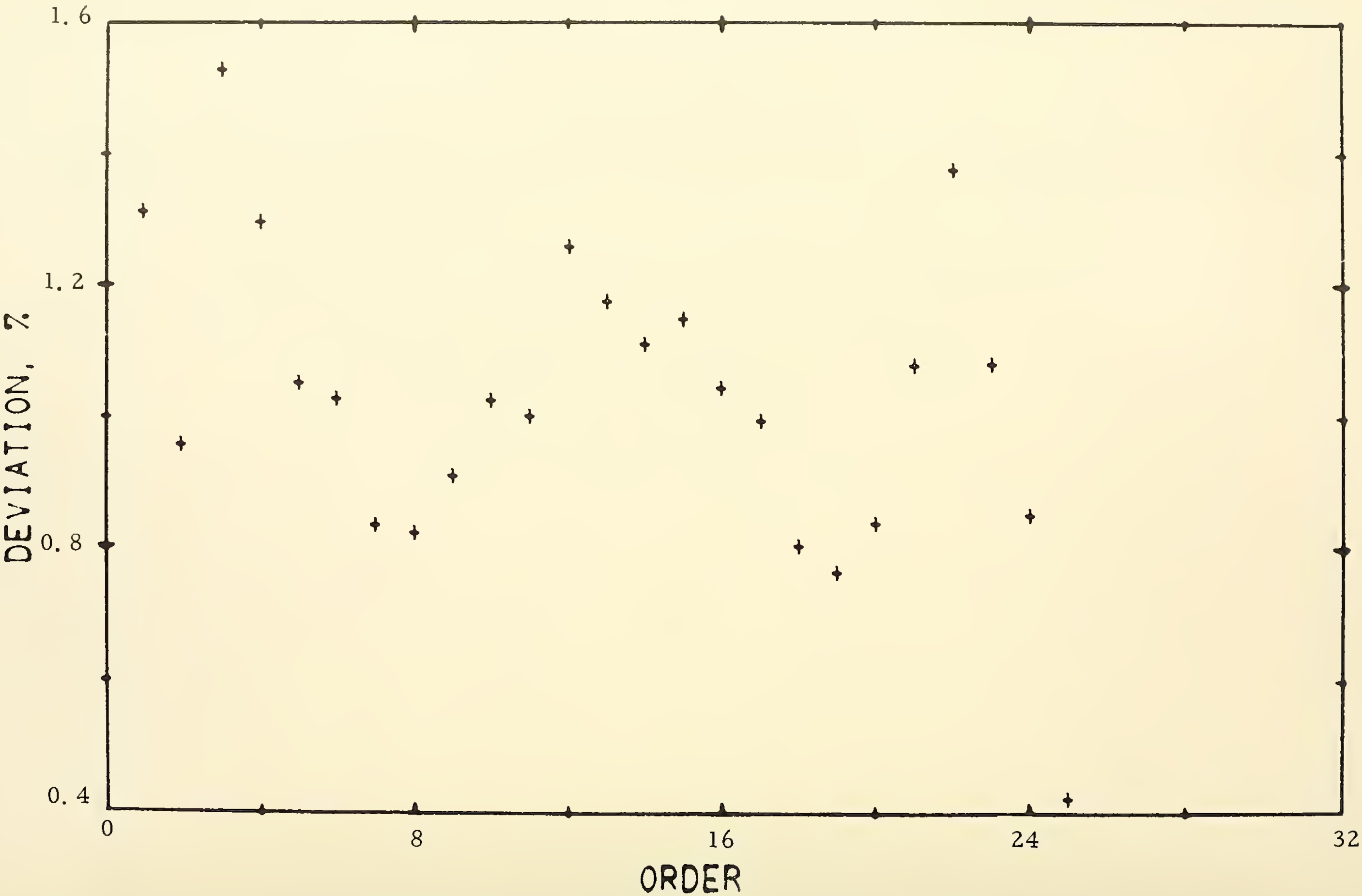

Figure 9D. Meter L, Performance vs. Order, Boundary Test.

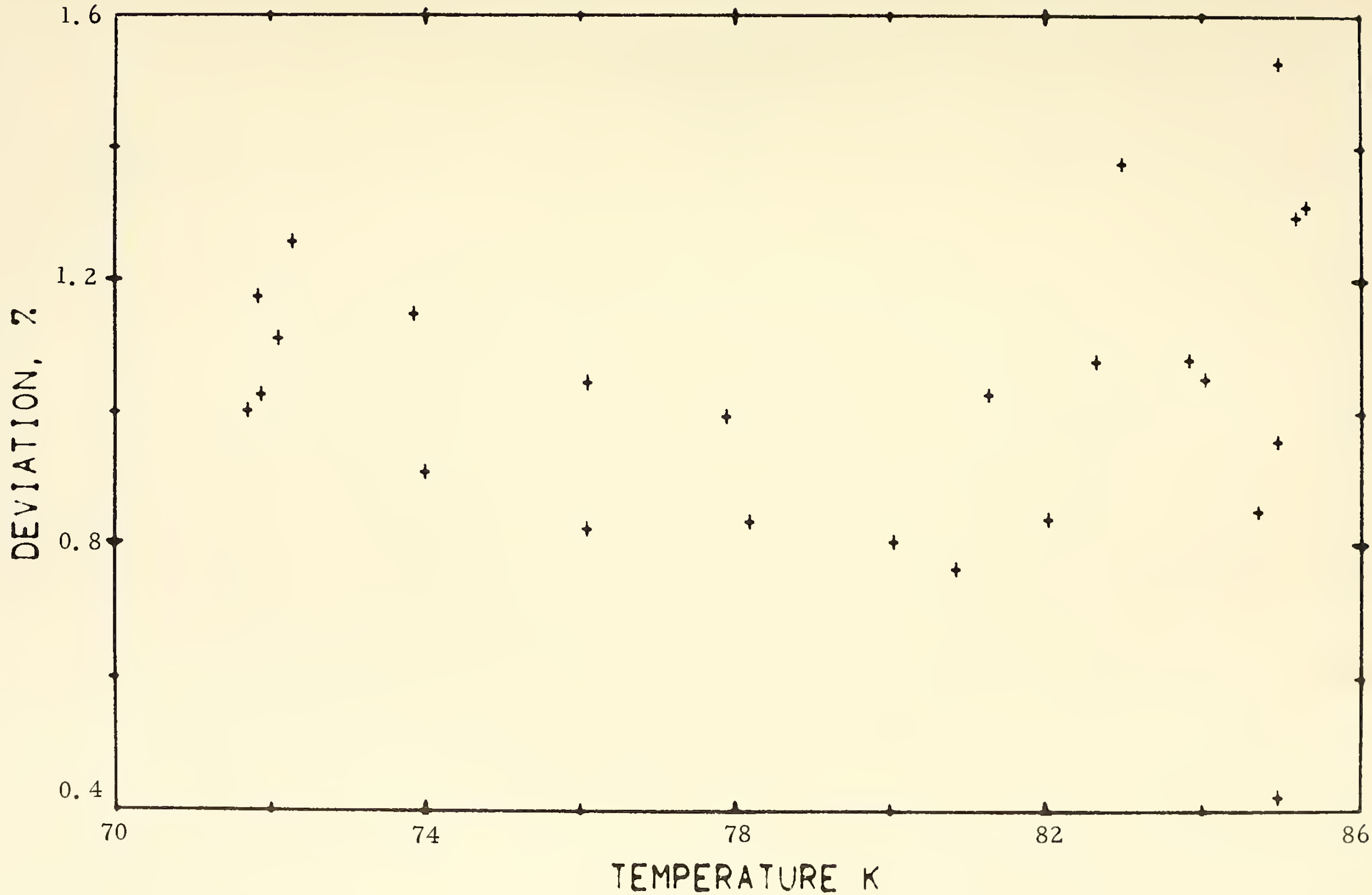

Figure 10D. Meter L, Performance vs. Temperature, Boundary Test.

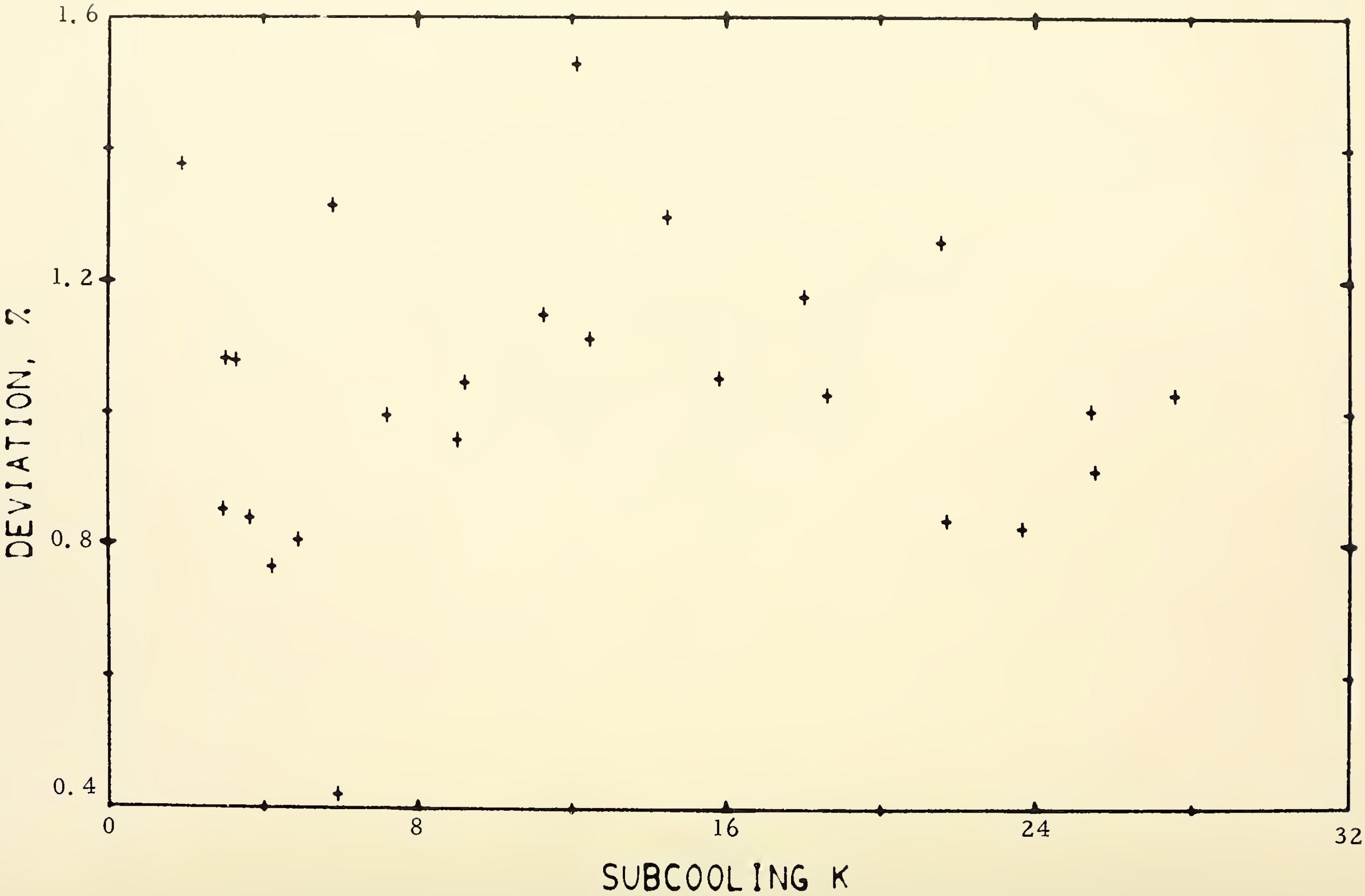

Figure 11D. Meter L, Performance vs. Subcooling, Boundary Test.

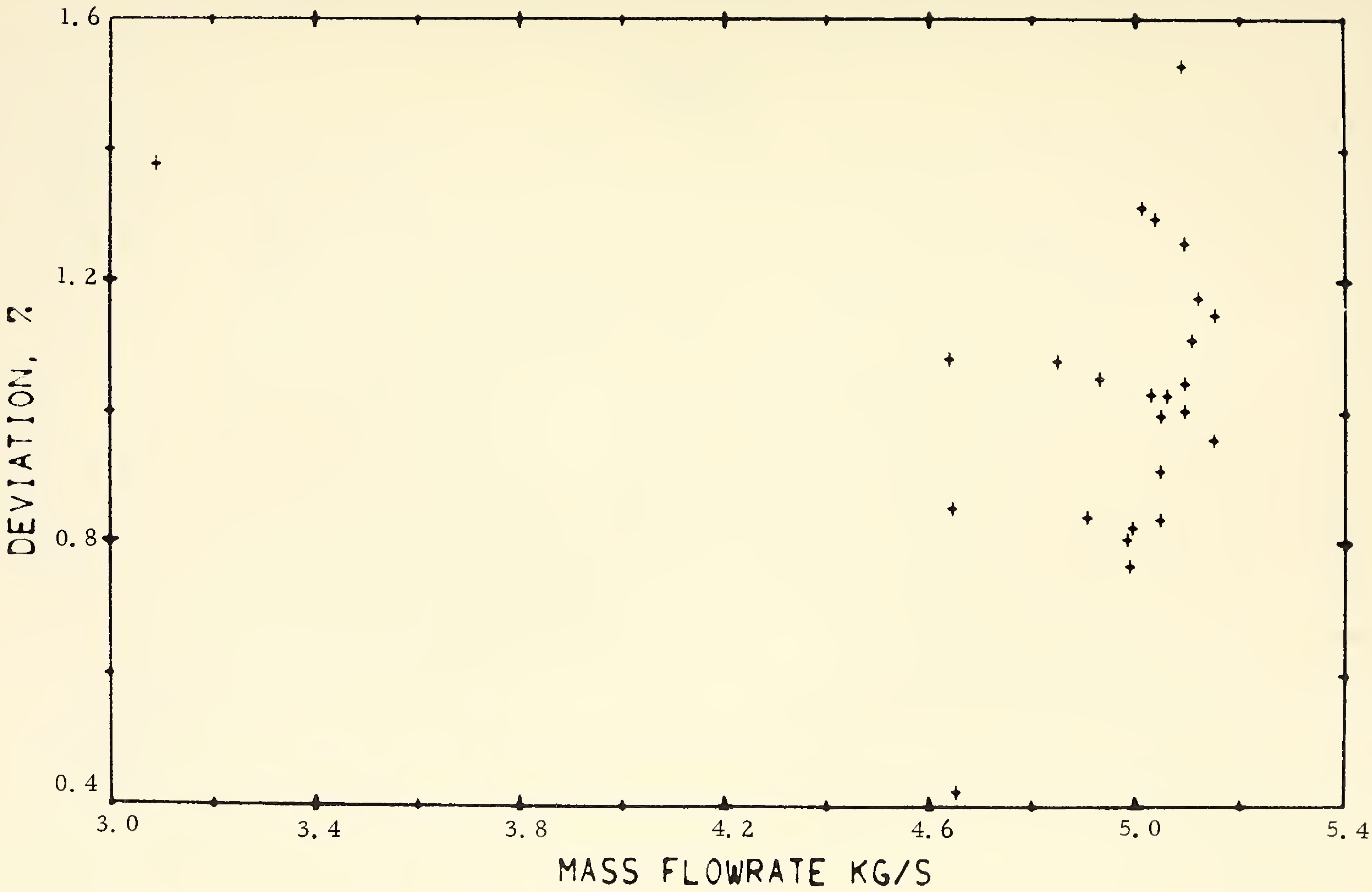

Figure 12D. Meter L, Performance vs. Mass Flow Rate, Boundary Test.

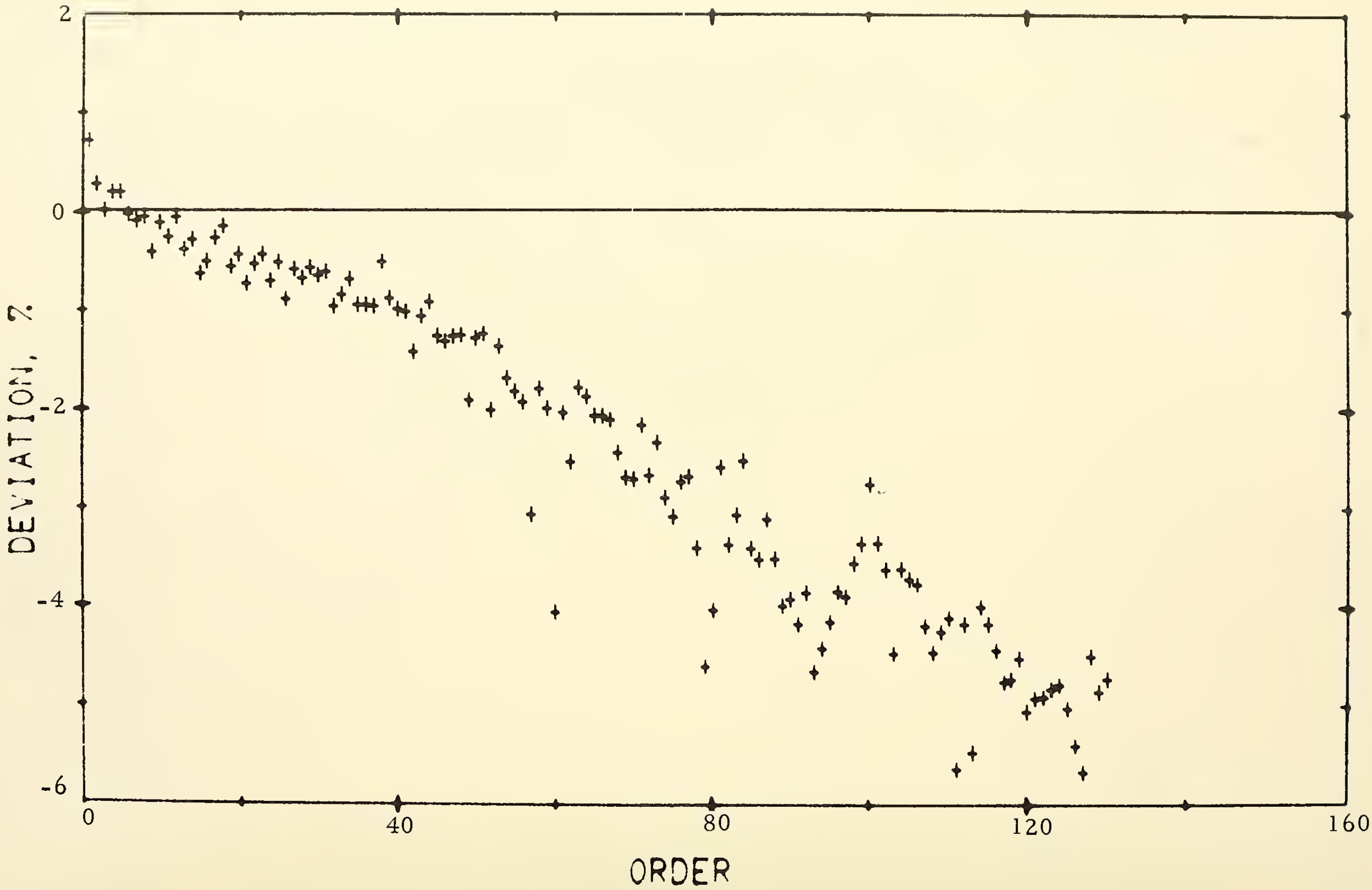

Figure 13D. Meter L, Performance vs. Order, Stability Test.

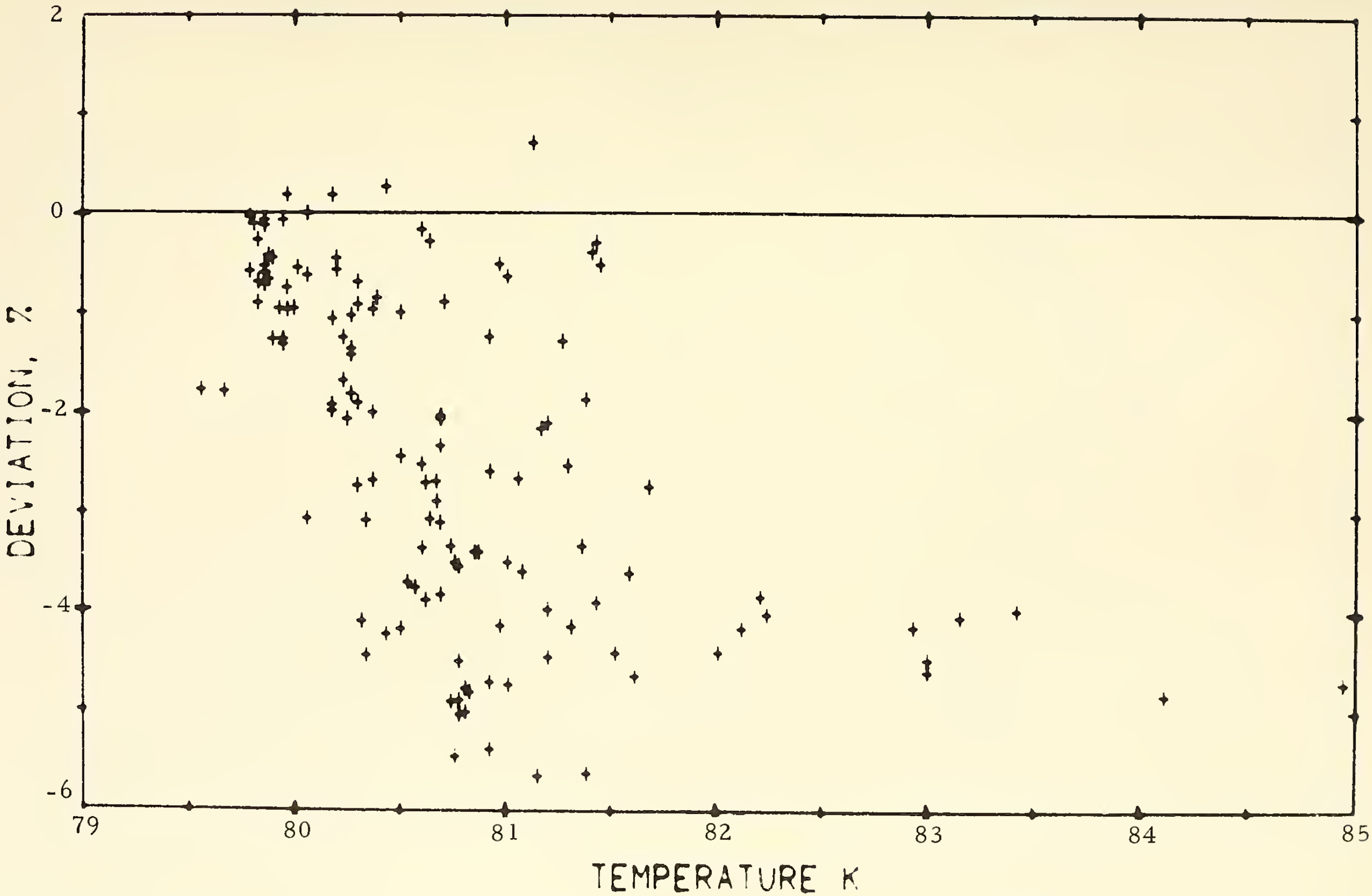

Figure 14D. Meter L, Performance vs. Temperature, Stability Test.

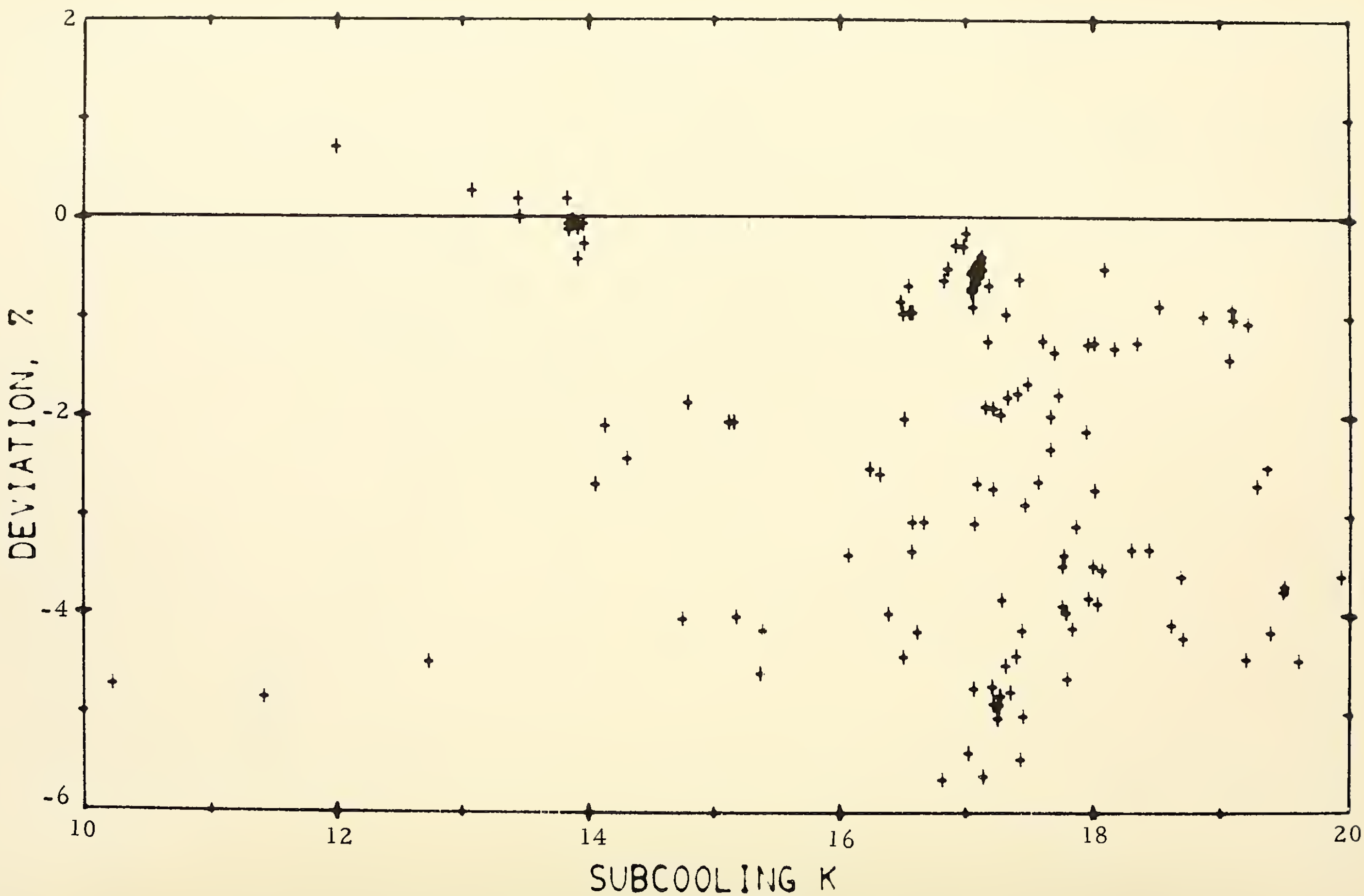

Figure 15D. Meter L, Performance vs. Subcooling, Stability Test.

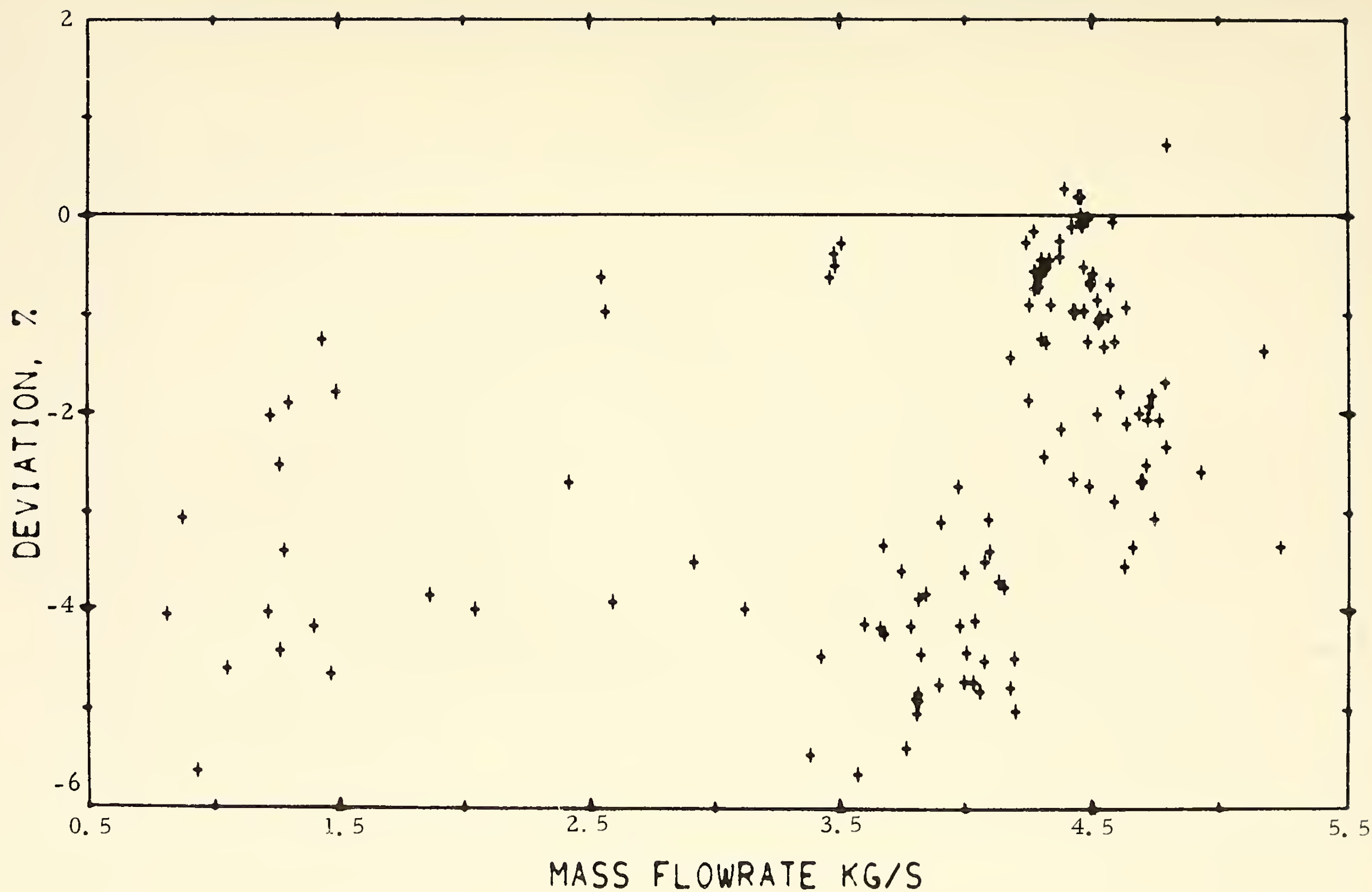

Figure 16D. Meter L, Performance vs. Mass Flow Rate, Stability Test.

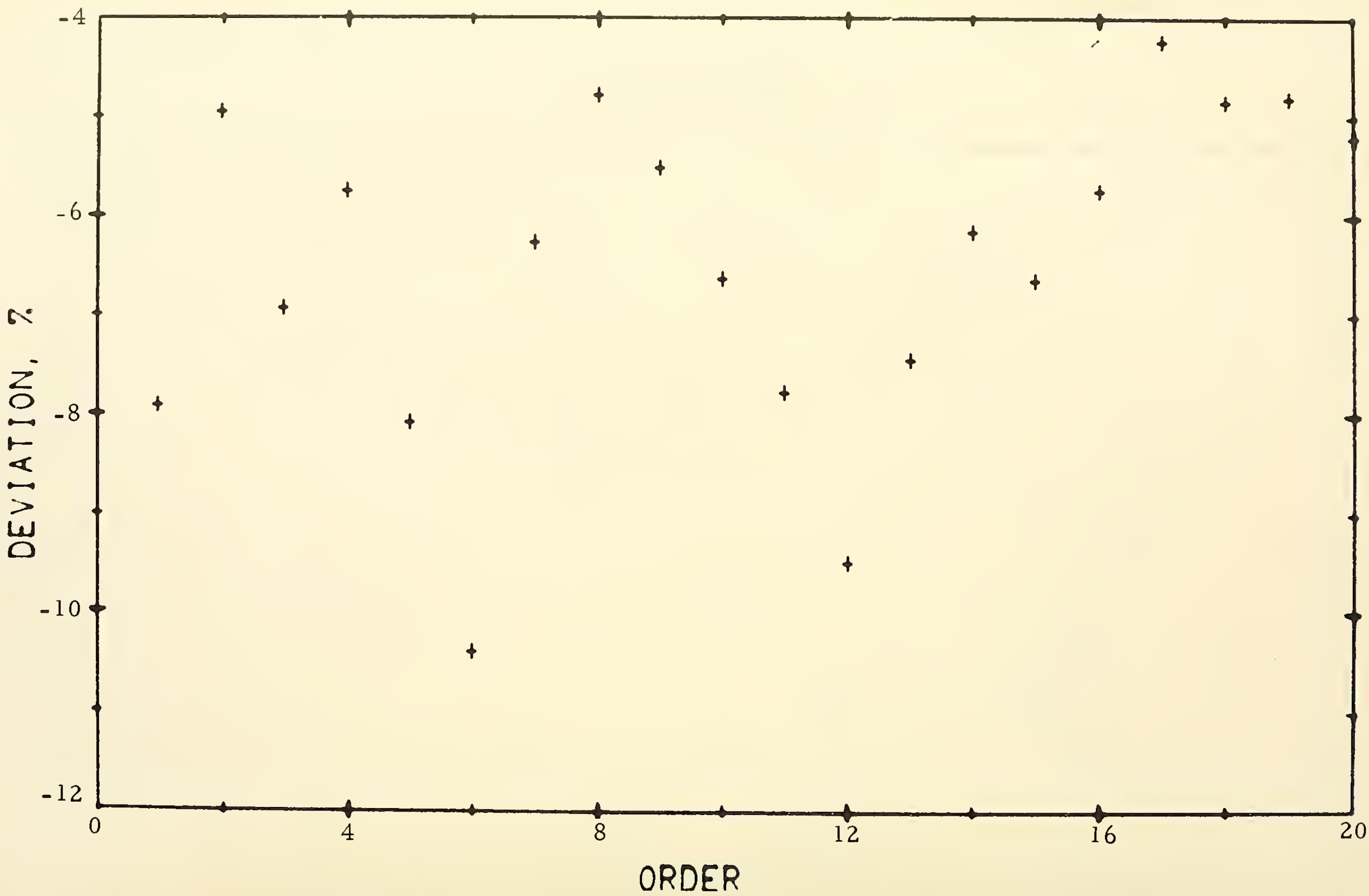

Figure 17D. Meter L, Performance vs. Order, Second Rangeability Test.

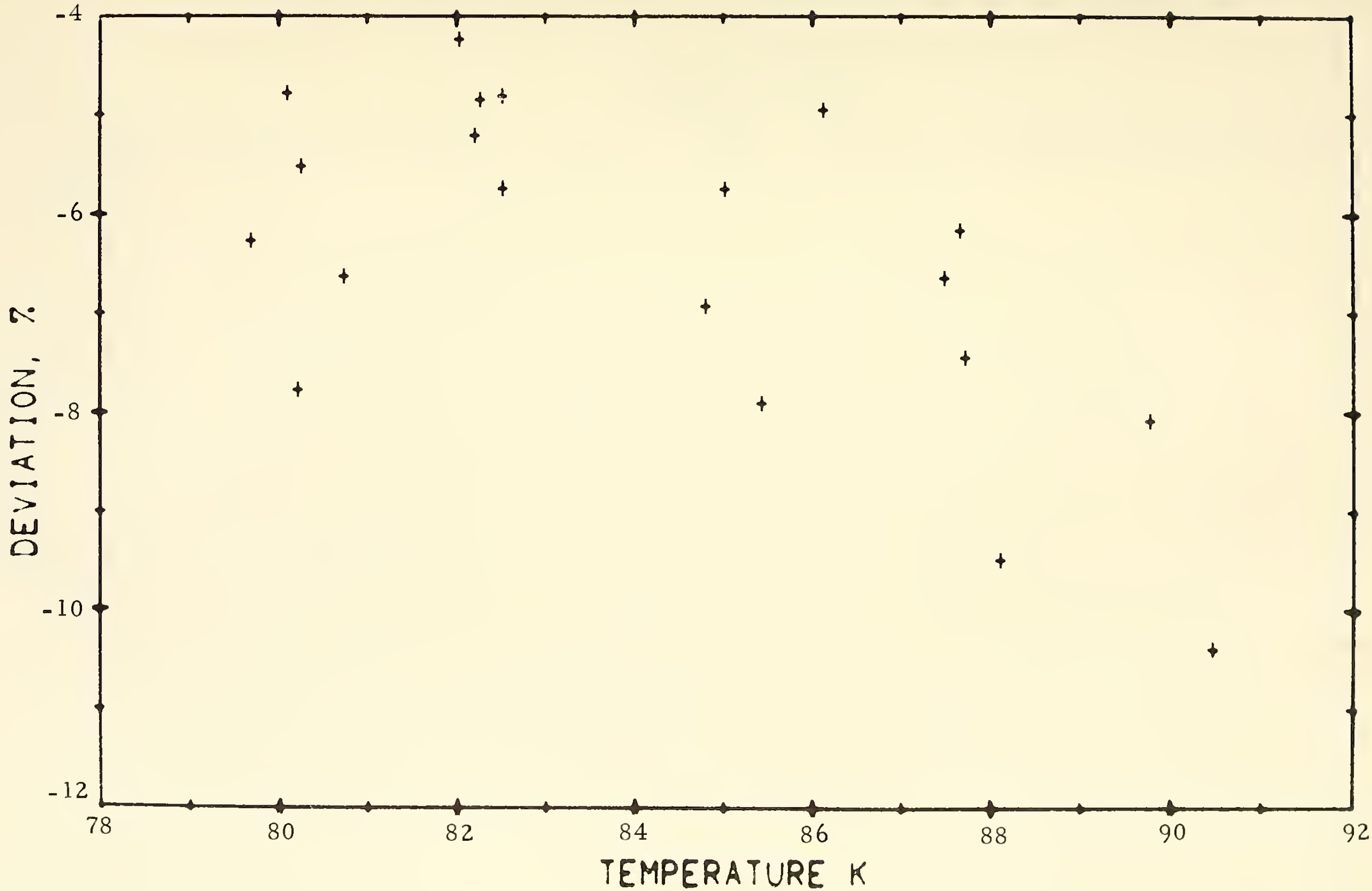

Figure 18D. Meter L, Performance vs. Temperature, Second Rangeability Test.

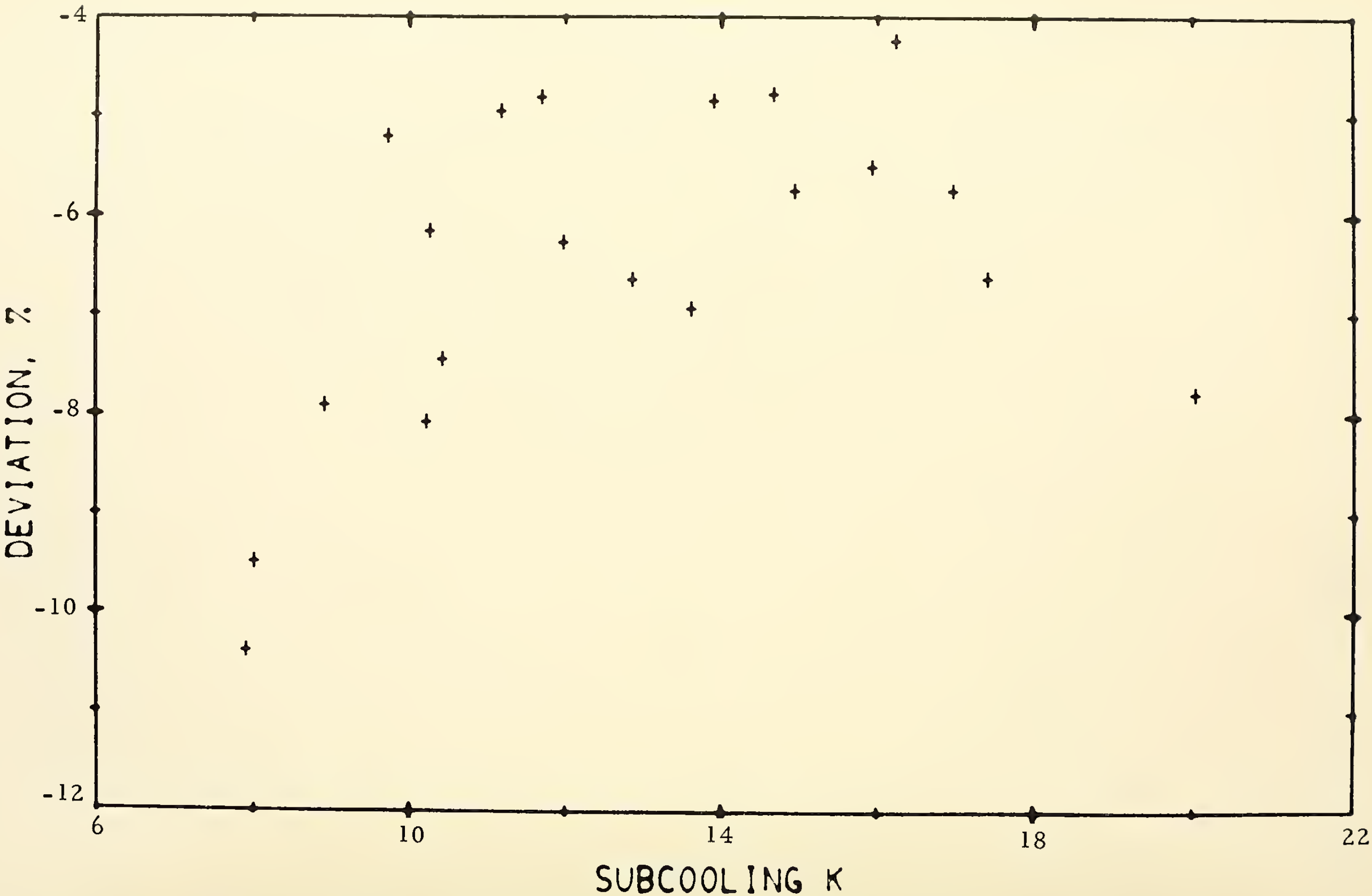

Figure 19D. Meter L, Performance vs. Subcooling, Second Rangeability Test.

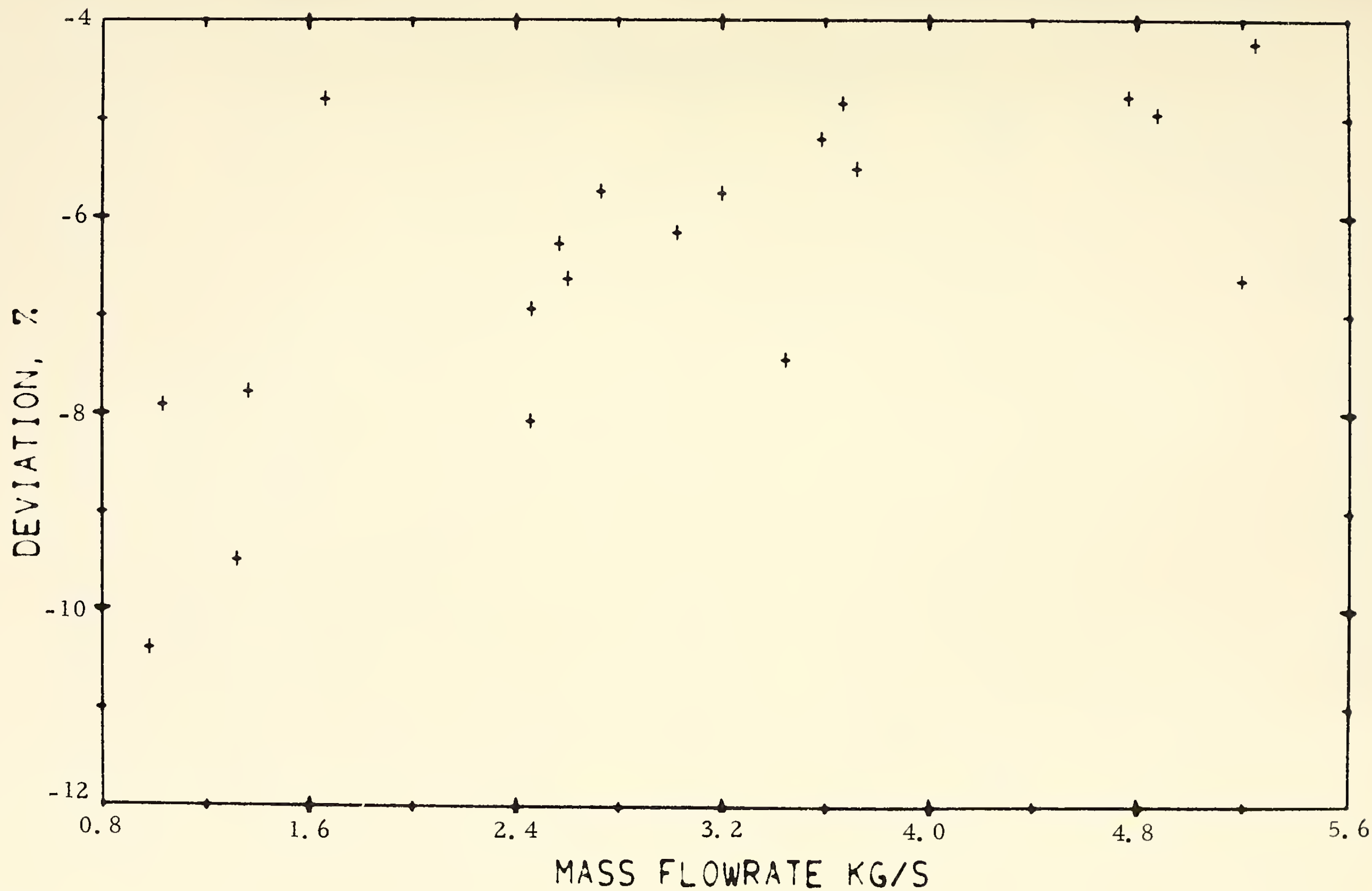

Figure 20D. Meter L, Performance vs. Mass Flow Rate, Second Rangeability Test.

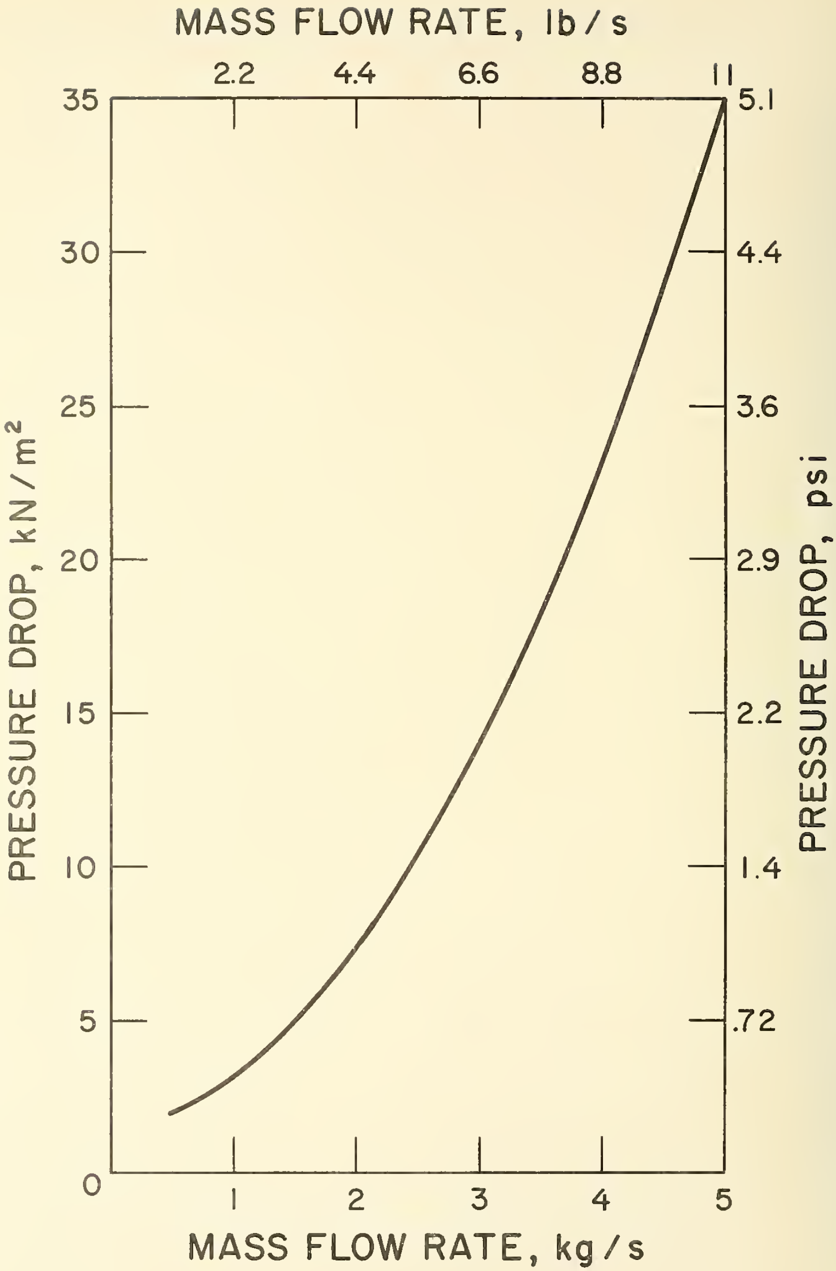

Figure 21D. Meter L Pressure Drop.

APPENDIX E. Performance of an Oscillating Piston Meter with a Mechanical Counter (Meters E and M)

This meter is illustrated in figure 1E. Liquid is admitted to the inlet and is first taken out the priming line to cool the meter to operating temperature. After priming, liquid flows through the piston assembly. Liquid enters the piston assembly through the inlet port and displaces the piston horizontally around the vertical axis. The piston is kept from turning by a slot that rides on a plate. The resulting motion is an oscillation that is geared to a mechanical register. Liquid passes out the discharge port to the meter outlet.

Three meters of this type were evaluated. One of these meters was designated as a one-inch nominal size meter, while the other two were designated as a one and one-half-inch nominal size meter. No specifications were provided with the one-inch meter (E); however, it was determined by talking with the meter supplier that the maximum flow rate should be limited to 0.003155 m^3/s (50 gpm). The nameplate specifications on the one and one-half inch meter (M) are:

size -- 0.0381 m (1-1/2 inch)
maximum flow rate -- 0.0044 m^3/s (70 gpm)
minimum flow rate -- 0.00088 m^3/s (14 gpm)
maximum pressure -- 2.413 MN/m^2 (350 psia)
material -- aluminum piston, brass case.

Meter E

This meter registers the swept volume of the positive displacement element in U. S. gallons (0.003785 m^3). Several pulsers were tried and a photo cell arrangement was selected that gave 0.01297 m^3/pulse (3.428 gallons/pulse). No meter design density information was specified; therefore, the volumetric meter factor was 0.01297 m^3/pulse (3.428 gallons/pulse).

Since the meter registration is in volume units, no density corrections are required to obtain the results shown in this report.

Deviation data from all tests for meter E are given in sequential order in figure 2E.

The results of the first rangeability test of meter E are shown by the scatter plots of figure 3E, 4E, 5E, and 6E. The fit of these data to the mathematical model is given in table 1E.

Table 1E. Fit of Model to Meter E, First Rangeability Test Data

Model $y = 13.02 - 0.135\ T$
Bias at $T = 80$ K, $y = +2.2\%$
Residual standard deviation $= \pm 0.57\%$
Number of points = 20

The only statistically significant dependency found was with temperature. The coefficients for T^2, $\dot{m}$, and $\dot{m}^2$ have been considered. The precision based on three times the standard deviation is ±1.7 percent and the bias is +2.2 percent at a temperature of 80 K.

The results of the boundary test of meter E are given in figures 7E, 8E, 9E, and 10E. A tendency to form vapor in the meter at a low subcooling is not seen in the data. However, the relatively large imprecision in these data may mask the presence of cavitation effects.

The results of the stability test are shown in figures 11E, 12E, 13E, and 14E. Figure 11E shows that an order dependency exists. The slope of a straight line fitted through these data is -0.0095%/point which gives a change in the deviation of -1.25 percent for the 132 points of the test.

The results of the second rangeability test are shown in the scatter plots of figures 15E, 16E, 17E, and 18E. The fit of the mathematical model to these data is given in table 2E.

Table 2E. Fit of Model to Meter E, Second Rangeability Test Data

Model $y = 206.9 - 4.78\ T + 0.02788\ T^2 - 0.516\ \dot{m}$
Bias at $T = 80$ K and $\dot{m} = 2.5$ kg/s, $y = +1.6\%$
Residual standard deviation $= \pm 0.51\%$
Number of points = 19

Significant dependencies were found with temperature, the square of temperature, and the mass flow rate. The coefficient for $\dot{m}^2$ was found not to be statistically significant. The precision based on three times the standard deviation is ±1.5 percent and the bias is +1.6 percent at a temperature of 80 K and a mass flow rate of 2.5 kg/s.

The pressure drop data are shown in figure 19E.

Meter M

Two 1-1/2 inch nominal size oscillating piston meters were evaluated, meters J and M. Meter J was subjected to the first rangeability test and the boundary test. This meter underwent a reduction in registration by about one percent during these tests and was replaced with meter M. Meter M was subjected to all tests.

This meter registers in mass units expressed in gallons (0.003785 m^3) of normal boiling point liquid. The registration may be defined in mass units by multiplying the density at the normal boiling point by the stated registration. Thus, the totalizing register mass units are 807.401 $kg/m^3 \times 0.0037854\ m^3 = 3.0563$ kg (6.7381 lbs) per gallon registered. Since the photo cell delivered one pulse for every five gallons, the mass meter factor was 15.2815 kg/pulse (33.6905 lb/pulse). The meter was designed to operate with liquid nitrogen at a density of 785.654 kg/m^3 (6.5566 lb/gal). The volumetric meter factor is the mass meter factor divided by the design density and is 0.019451 m^3/pulse (5.1384 gal/pulse).

Since the meter registration is in equivalent mass units, density corrections are required to obtain the results shown in this report.

The data from all tests for meter M are given in figure 20E where the deviation as a function of the order is shown.

The results of the first rangeability test are shown in the scatter plots of figures 21E, 22E, 23E, and 24E. The fit of these data to the mathematical model is given in Table 3E.

Table 3E. Fit of Model to Meter M, First Rangeability Test Data

Model $y = 1.33$
Bias, $y = +1.33\%$
Residual standard deviation $= \pm 0.21\%$
Number of points $= 19$

No statistically significant dependency was found; however, the coefficients for T, T^2, $\dot{m}$, and $\dot{m}^2$ were considered. The precision based on three times the standard deviation is ±0.63 percent and the bias is +1.33 percent.

The results of the boundary test are given in the scatter plots of figures 25E, 26E, 27E, and 28E. No subcooling dependency is seen in figure 27E even at the lowest value of 5 K.

The results of the stability test are given in figures 29E, 30E, 31E, and 32E. An order dependency is seen in figure 29E. A better view of this dependency is given in

figure 20E. Here it may be seen that the deviations shifted toward underregistration by about 3/4 of a percent in a relatively short time.

The results of the second rangeability test are given by the scatter plots of figures 33E, 34E, 35E, and 36E. The fit of these data to the mathematical model is given in table 4E.

Table 4E. Fit of Model to Meter M, Second Rangeability Test Data

Model y = 0.61
Bias, y = +0.61%
Residual standard deviation = ±0.18%
Number of points = 19

Again no statistically significant dependencies were found; however, the coefficients for T, T^2, $\dot{m}$, and $\dot{m}^2$ were considered. The precision based on three times the standard deviation is ±0.54 percent and the bias is +0.61 percent.

Meter pressure drop data are shown in figure 37E.

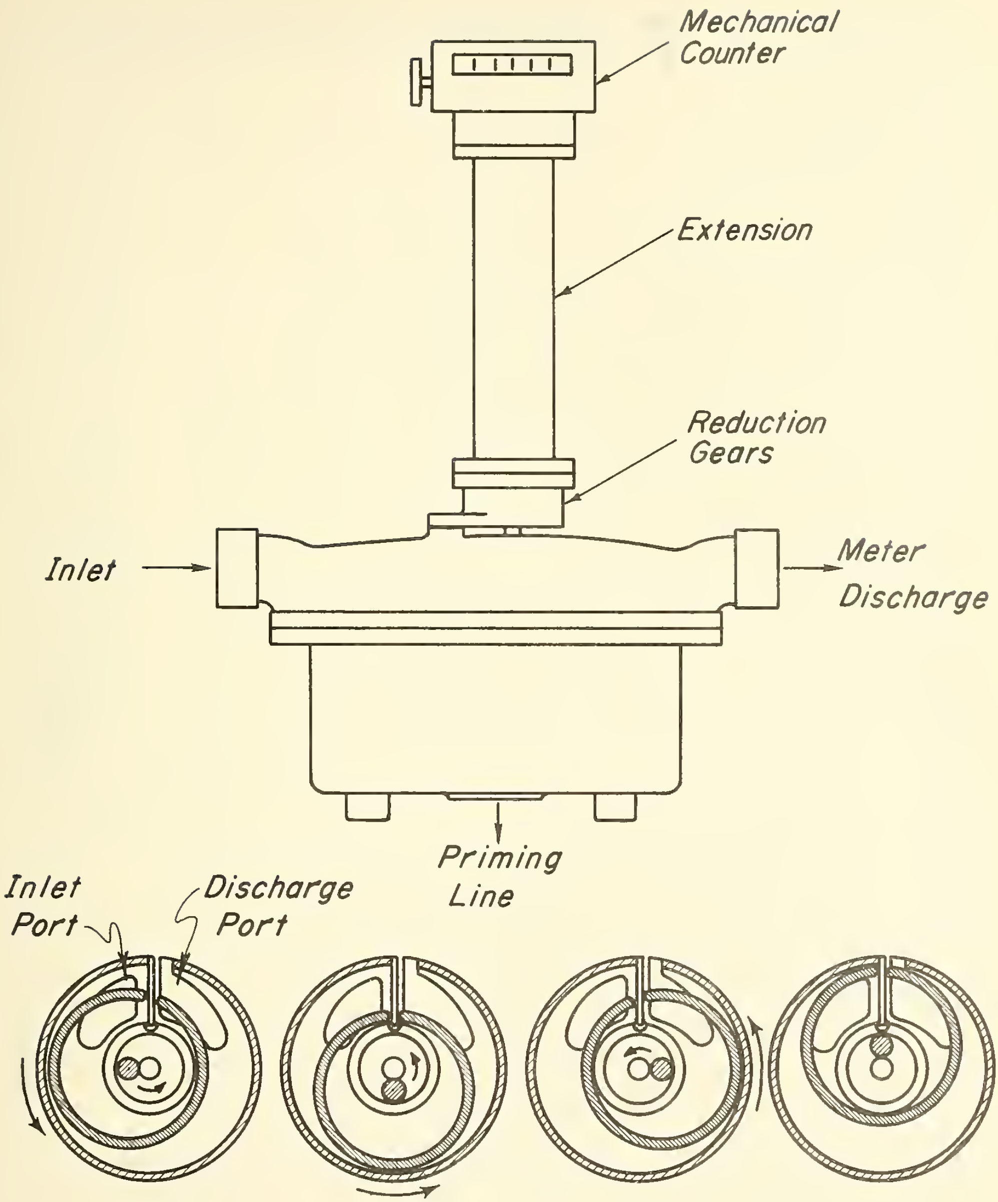

Figure 1E. Oscillating Piston Meter.

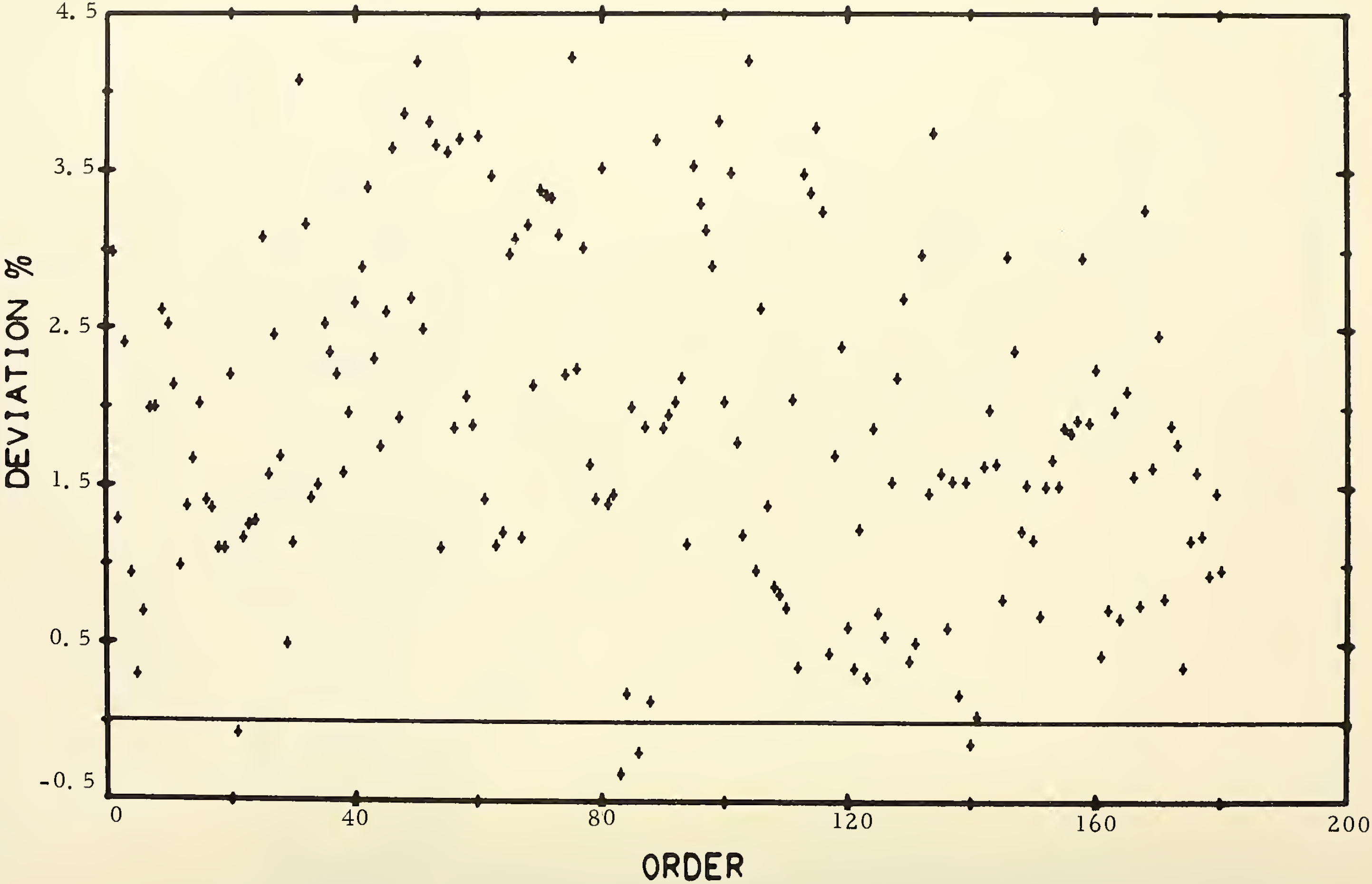

Figure 2E. Meter E, Performance Data from all Tests.

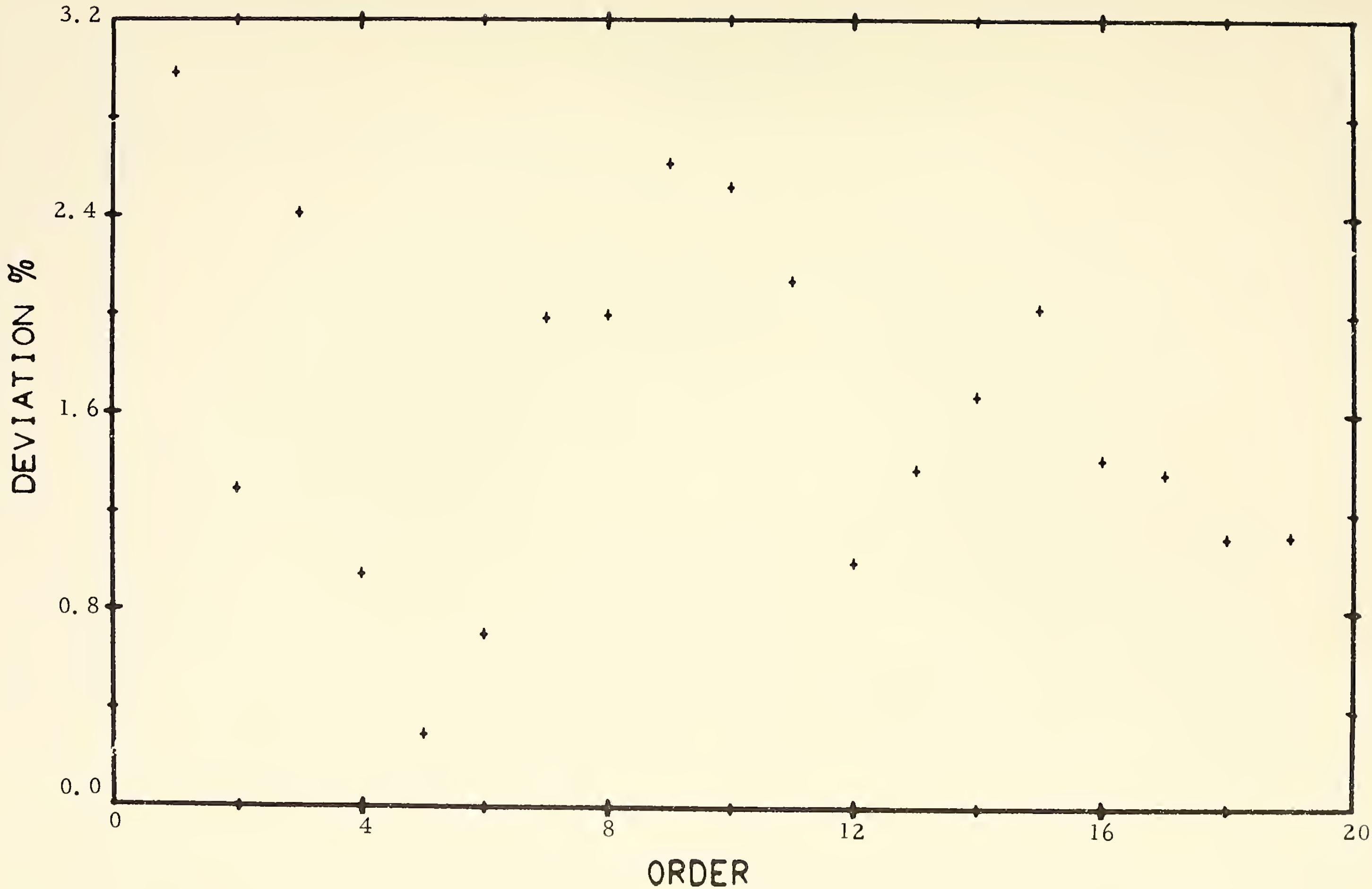

Figure 3E. Meter E, Performance vs. Order, First Rangeability Test.

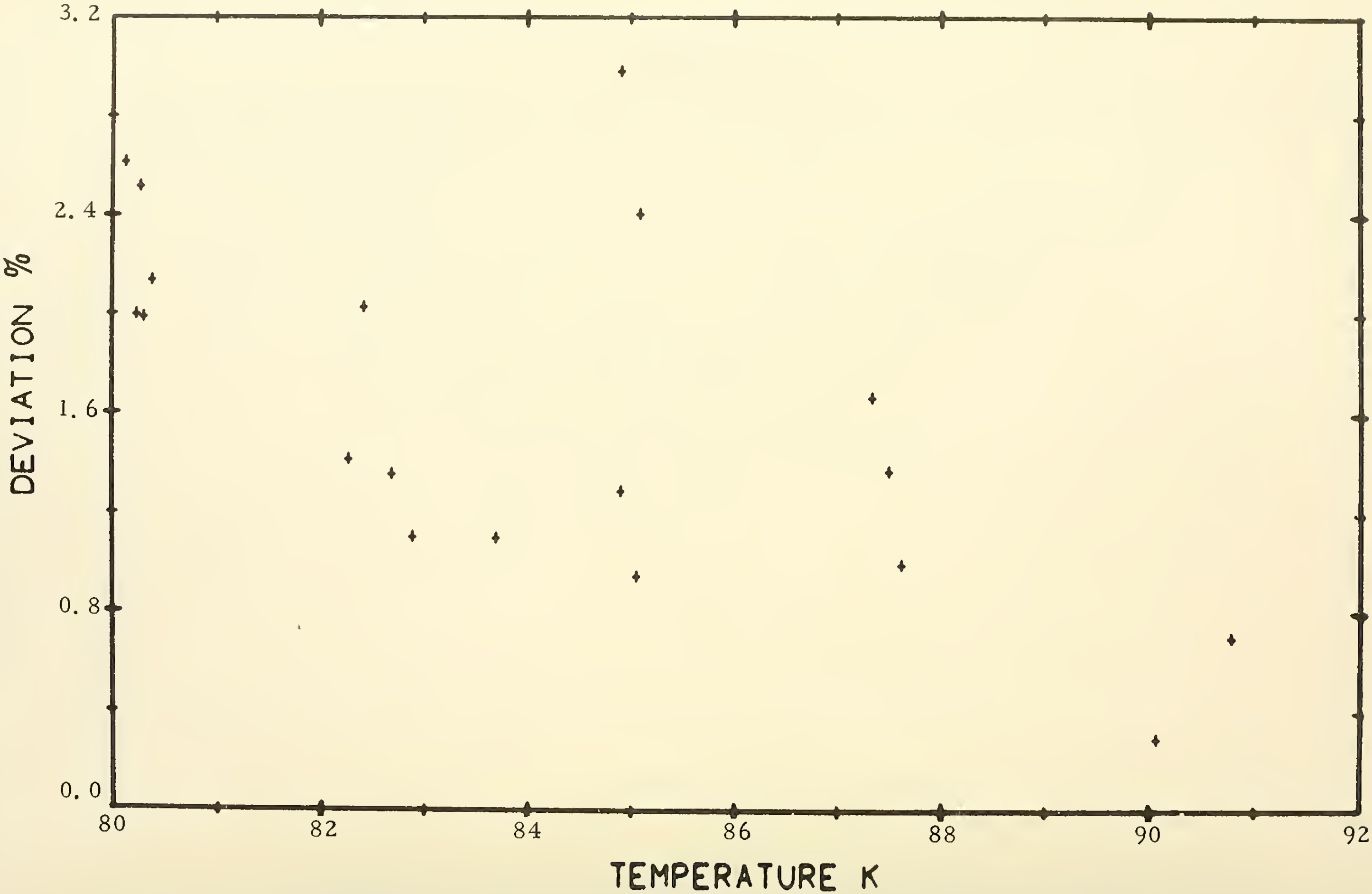

Figure 4E. Meter E, Performance vs. Temperature, First Rangeability Test.

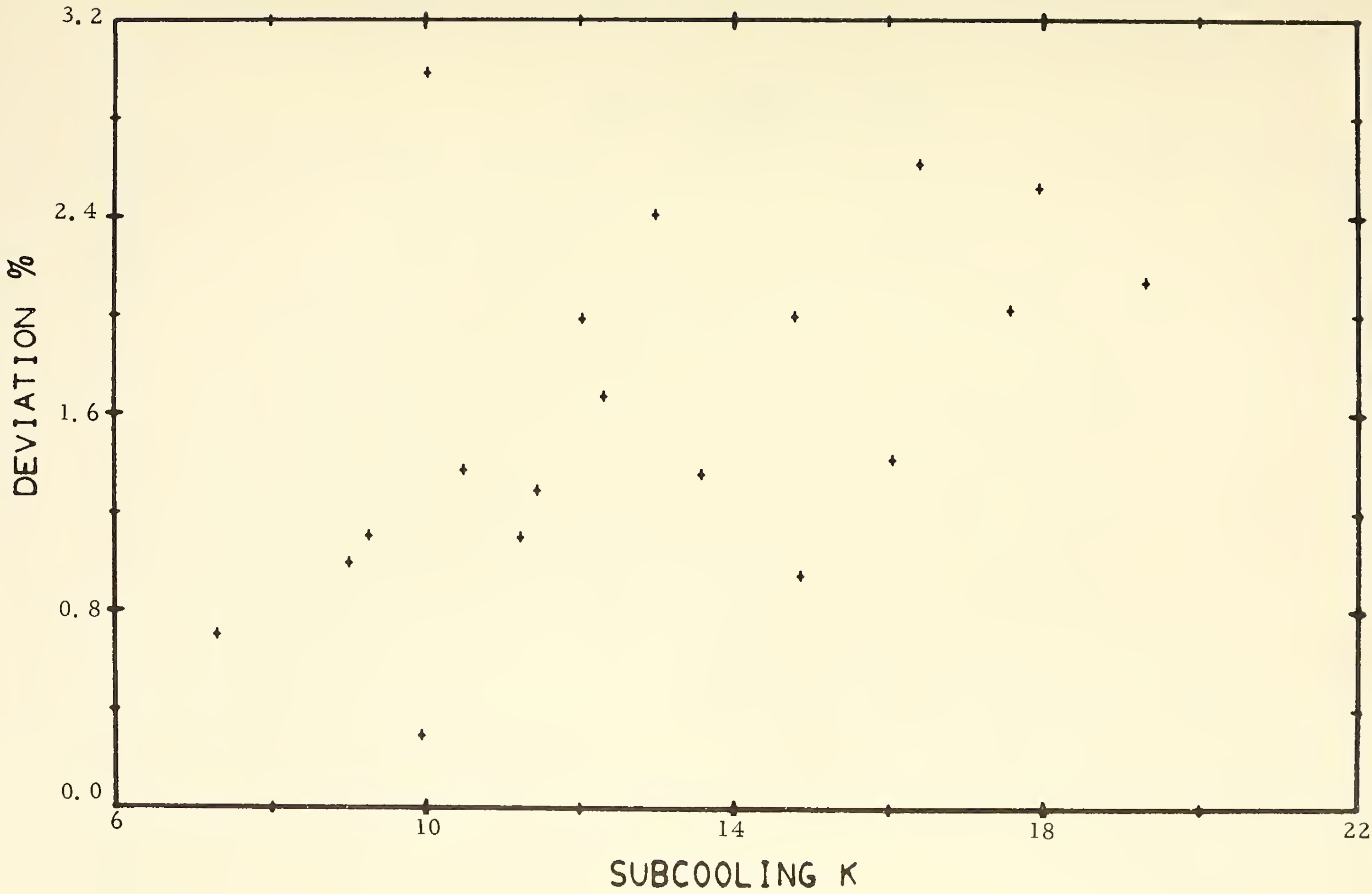

Figure 5E. Meter E, Performance vs. Subcooling, First Rangeability Test.

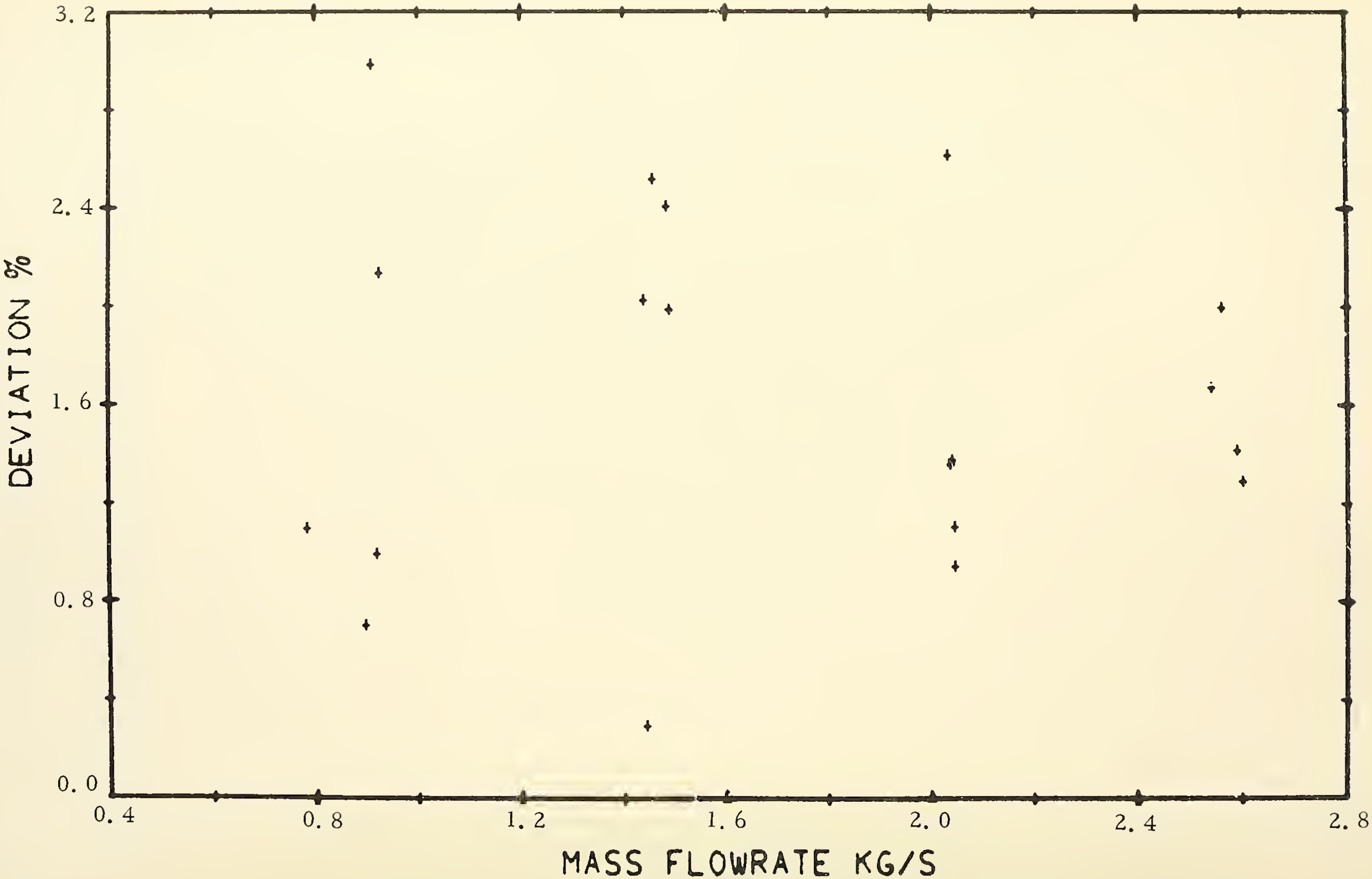

Figure 6E. Meter E, Performance vs. Mass Flow Rate, First Rangeability Test.

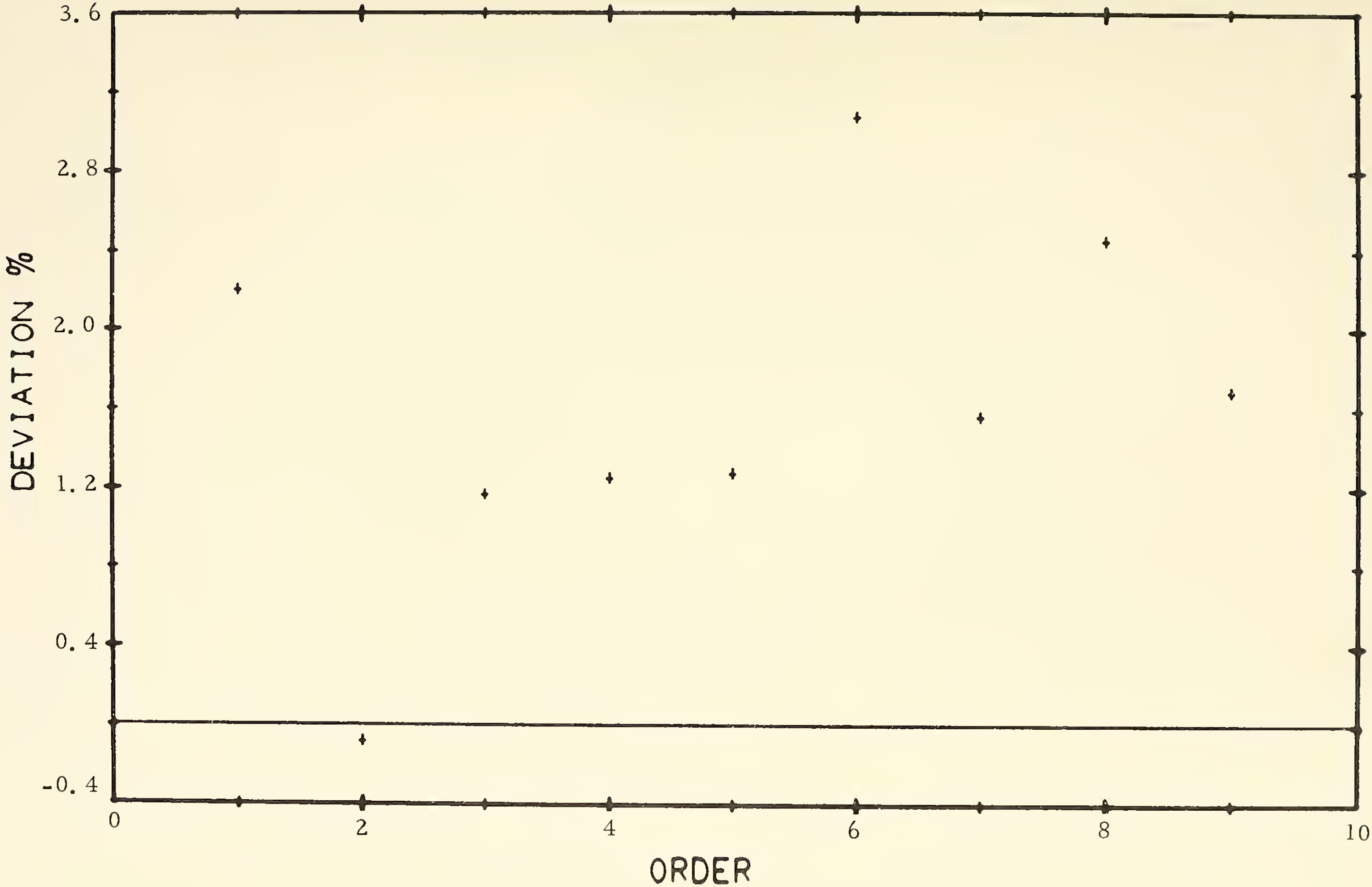

Figure 7E. Meter E, Performance vs. Order, Boundary Test.

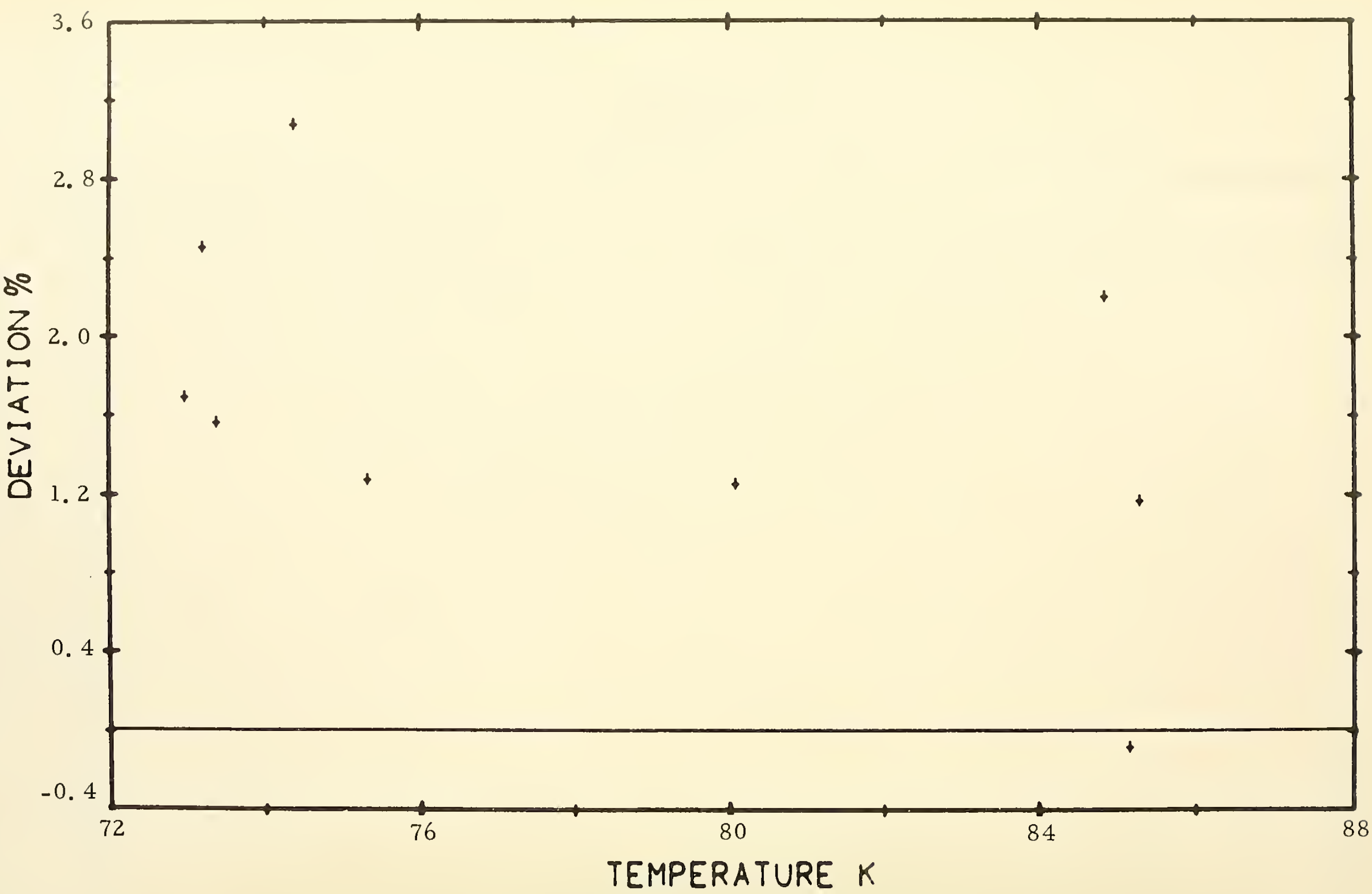

Figure 8E. Meter E, Performance vs. Temperature, Boundary Test.

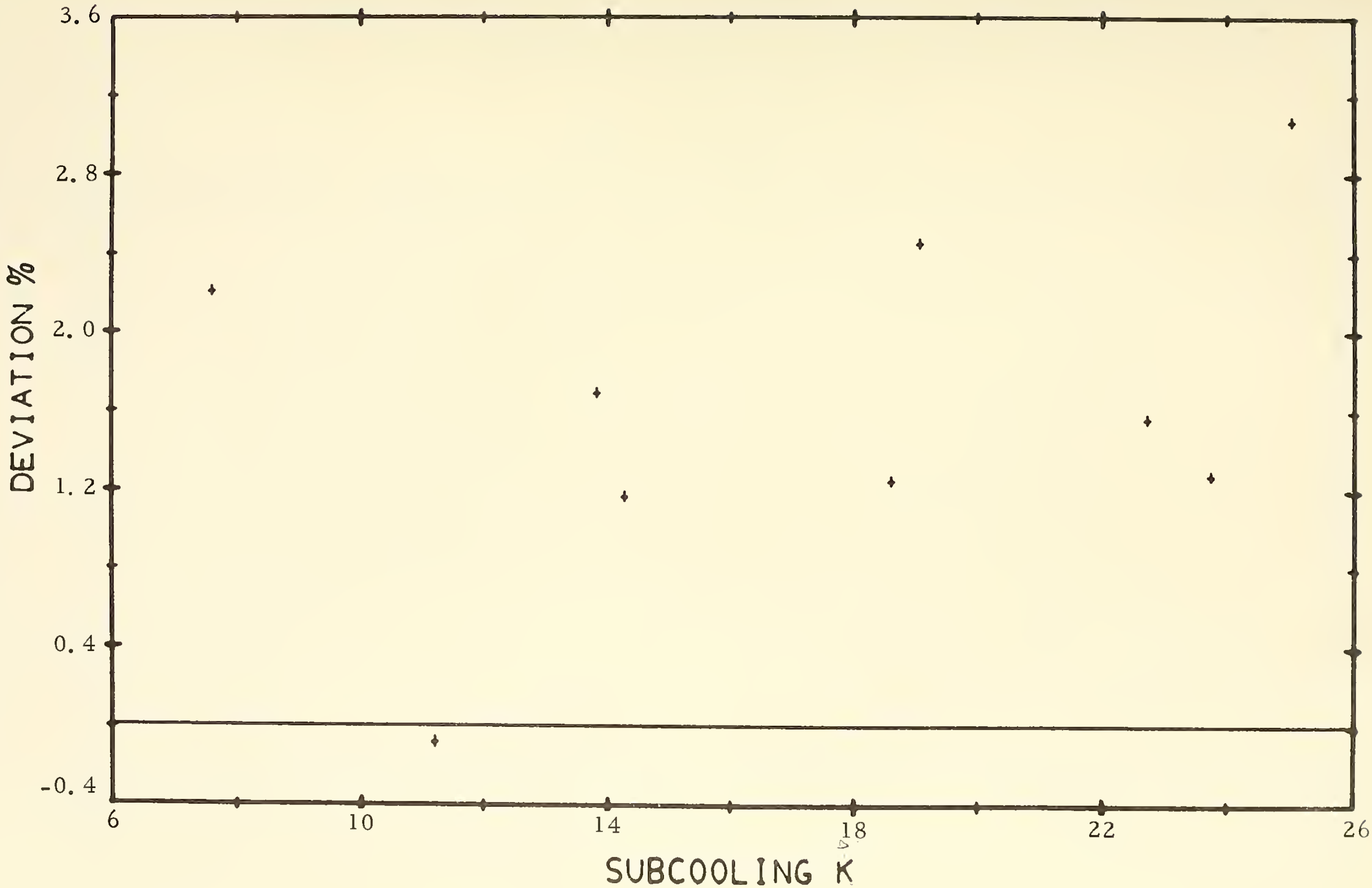

Figure 9E. Meter E, Performance vs. Subcooling, Boundary Test.

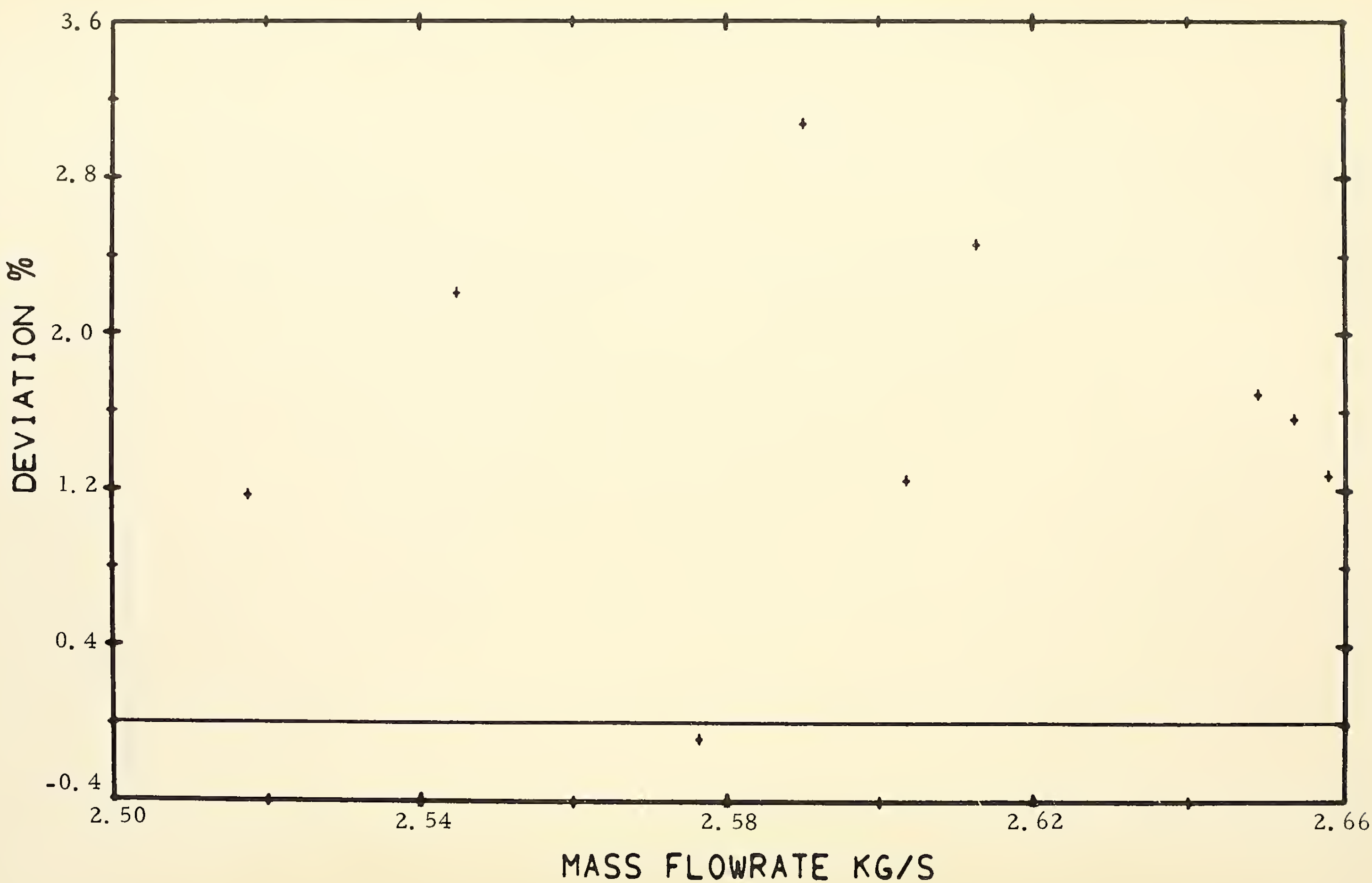

Figure 10E. Meter E, Performance vs. Mass Flow Rate, Boundary Test.

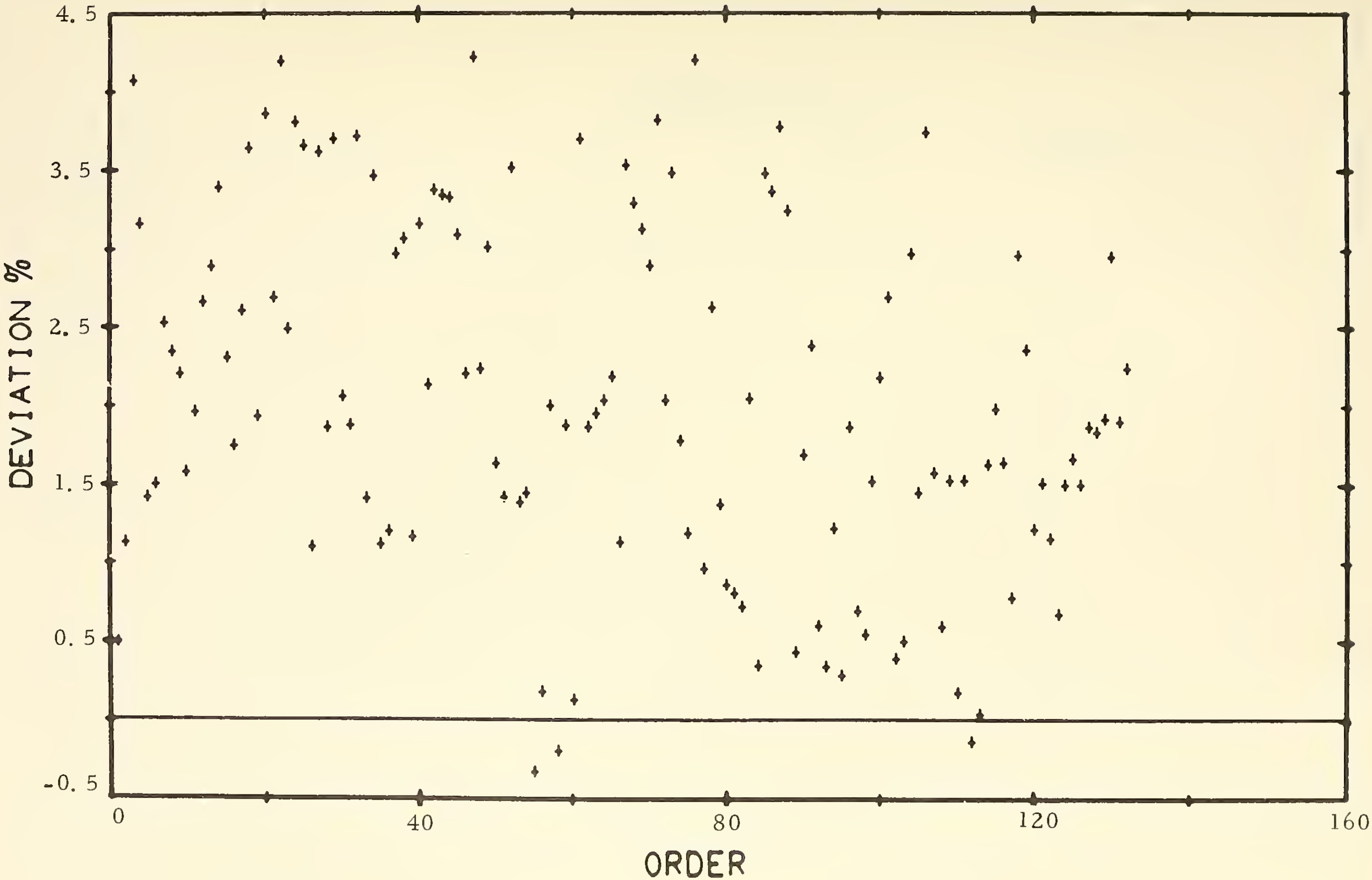

Figure 11E. Meter E, Performance vs. Order, Stability Test.

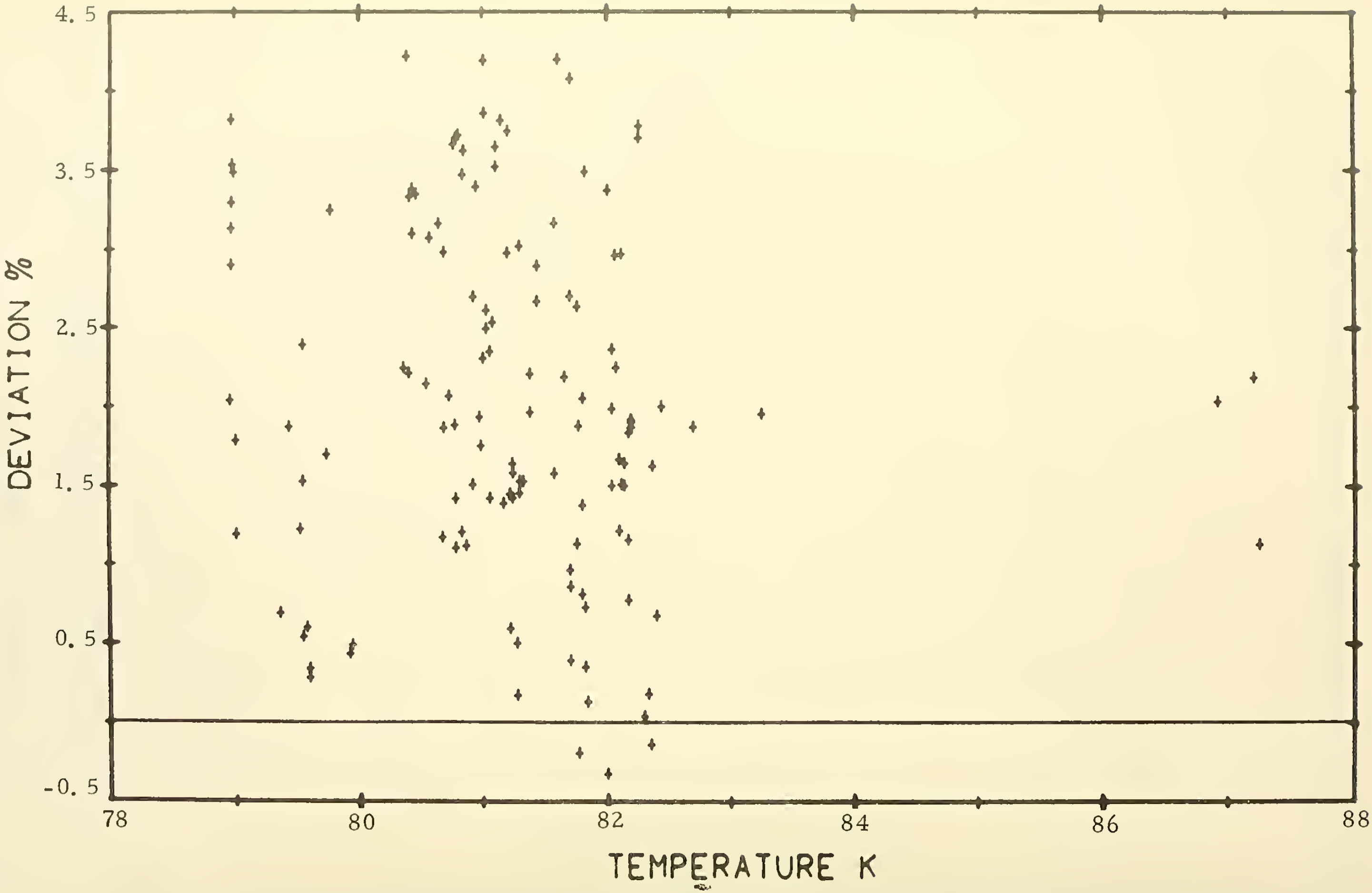

Figure 12E. Meter E, Performance vs. Temperature, Stability Test.

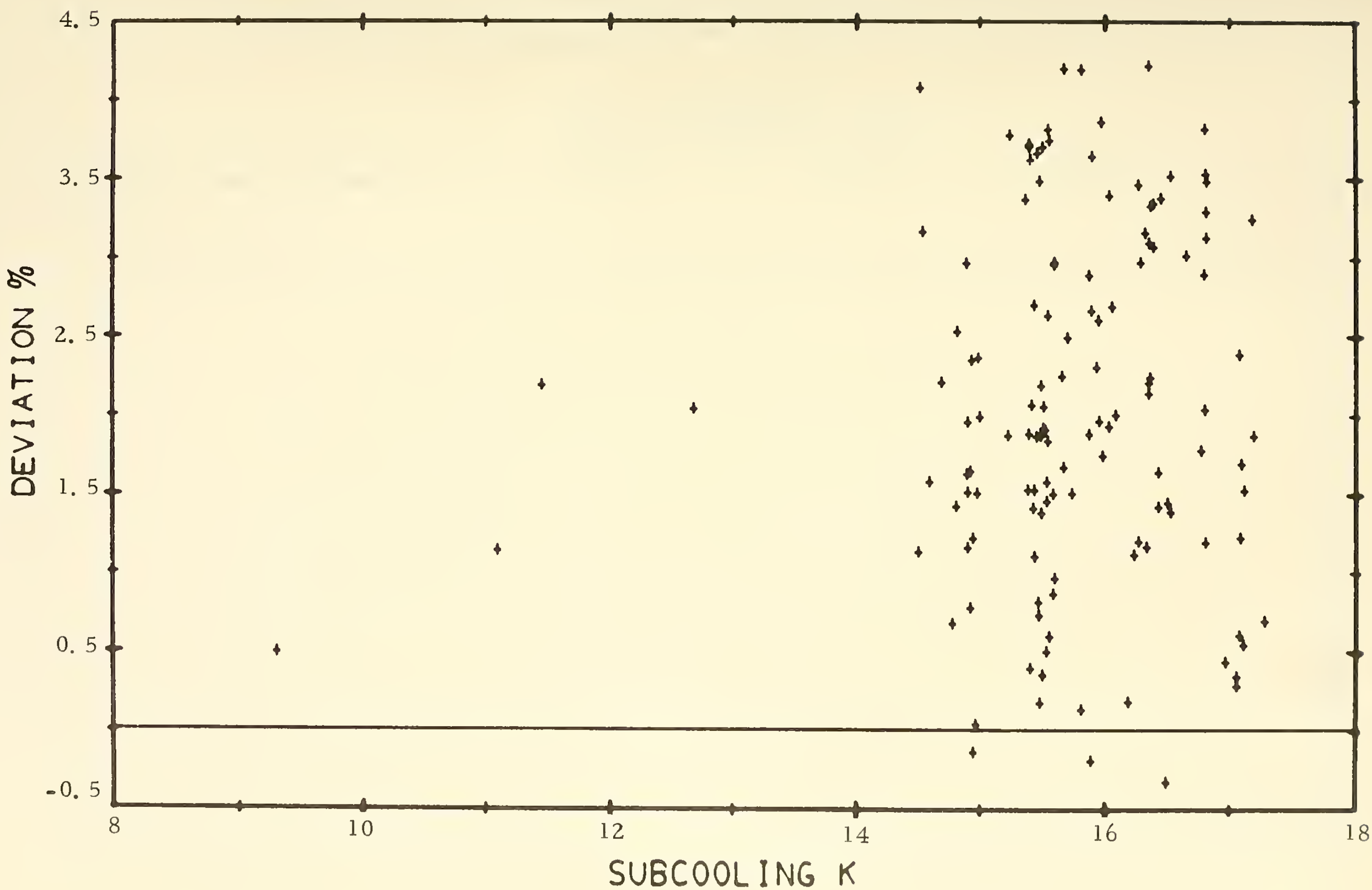

Figure 13E. Meter E, Performance vs. Subcooling, Stability Test.

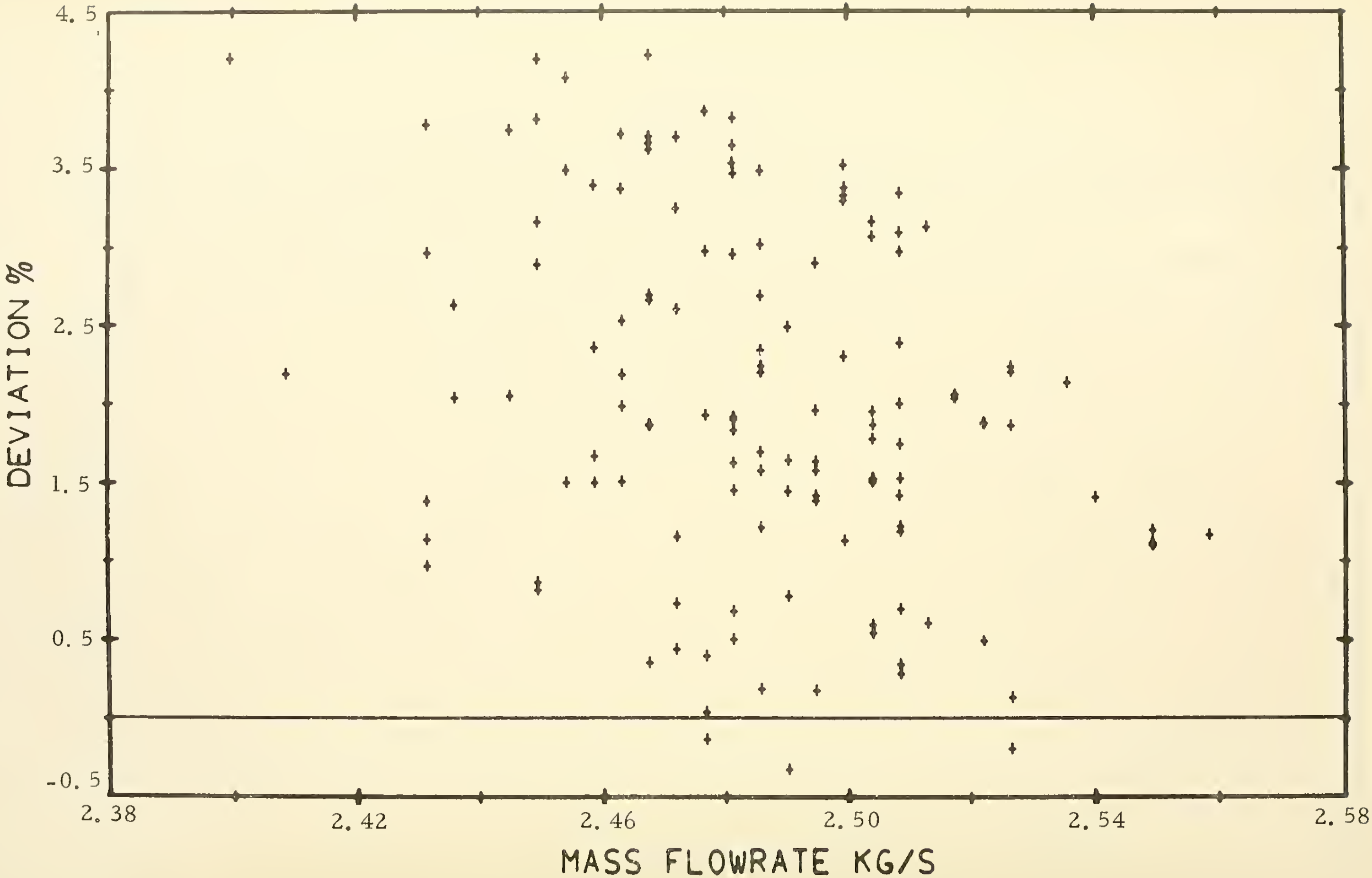

Figure 14E. Meter E, Performance vs. Mass Flow Rate, Stability Test.

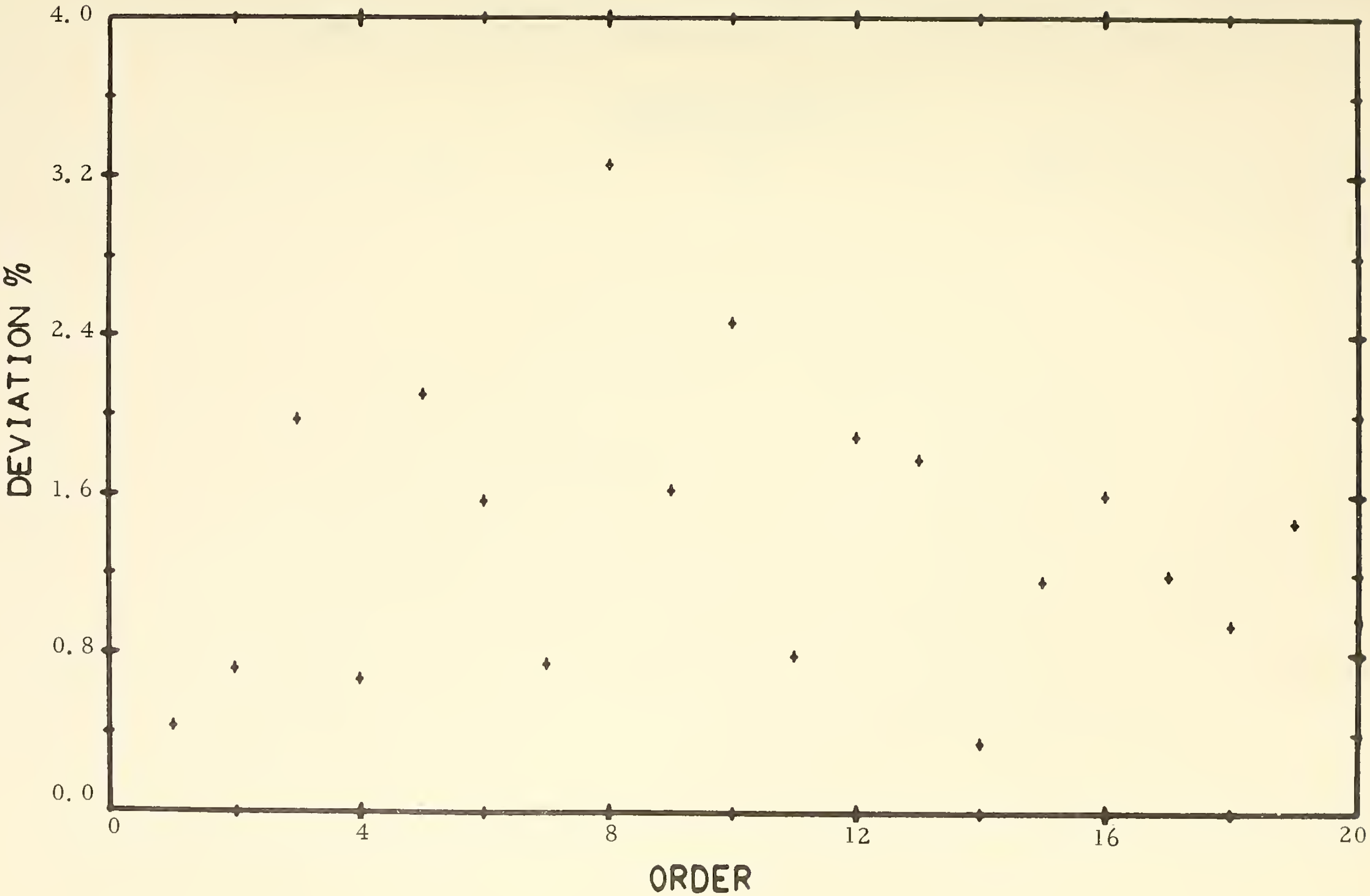

Figure 15E. Meter E, Performance vs. Order, Second Rangeability Test.

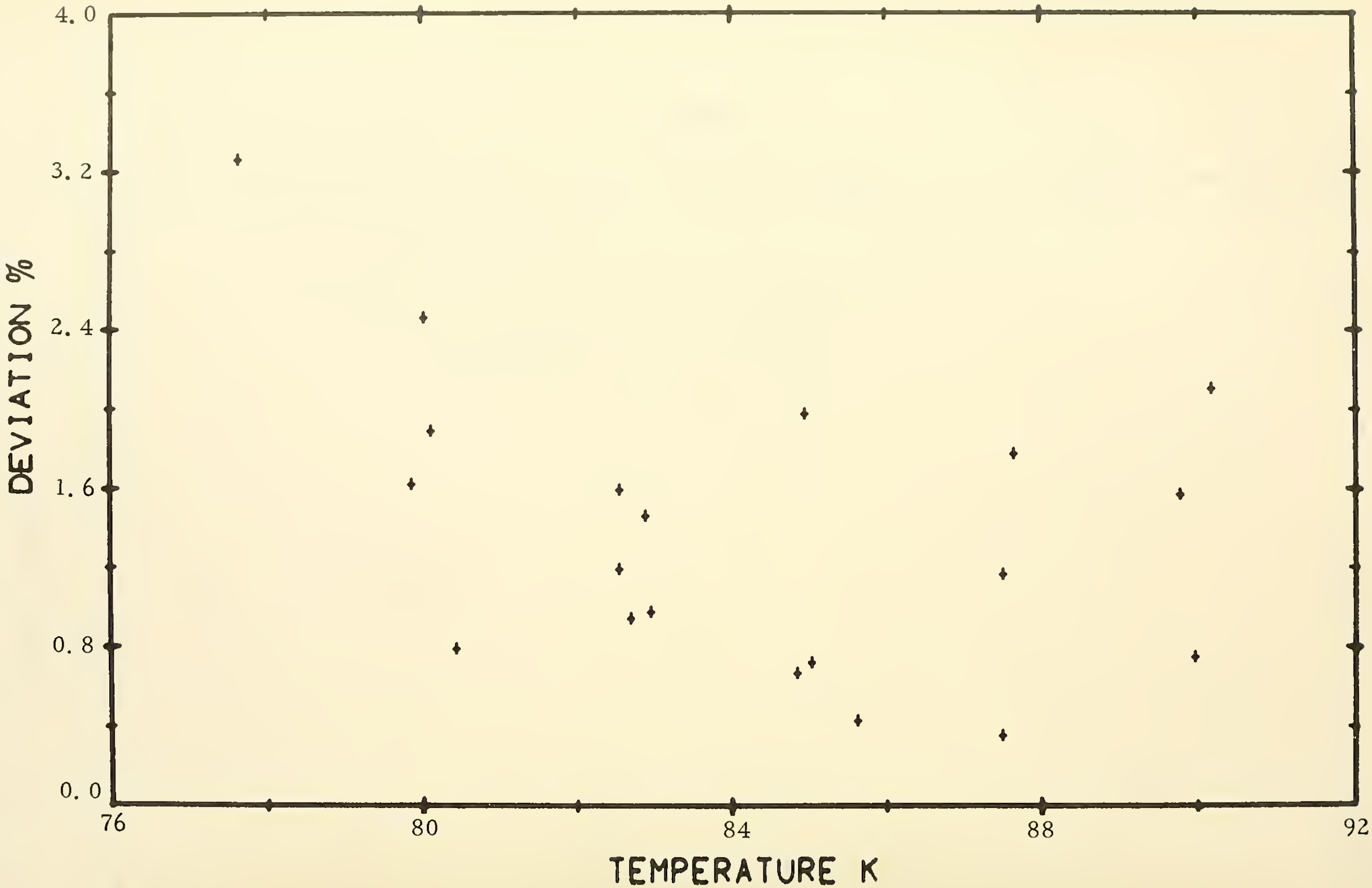

Figure 16E. Meter E, Performance vs. Temperature, Second Rangeability Test.

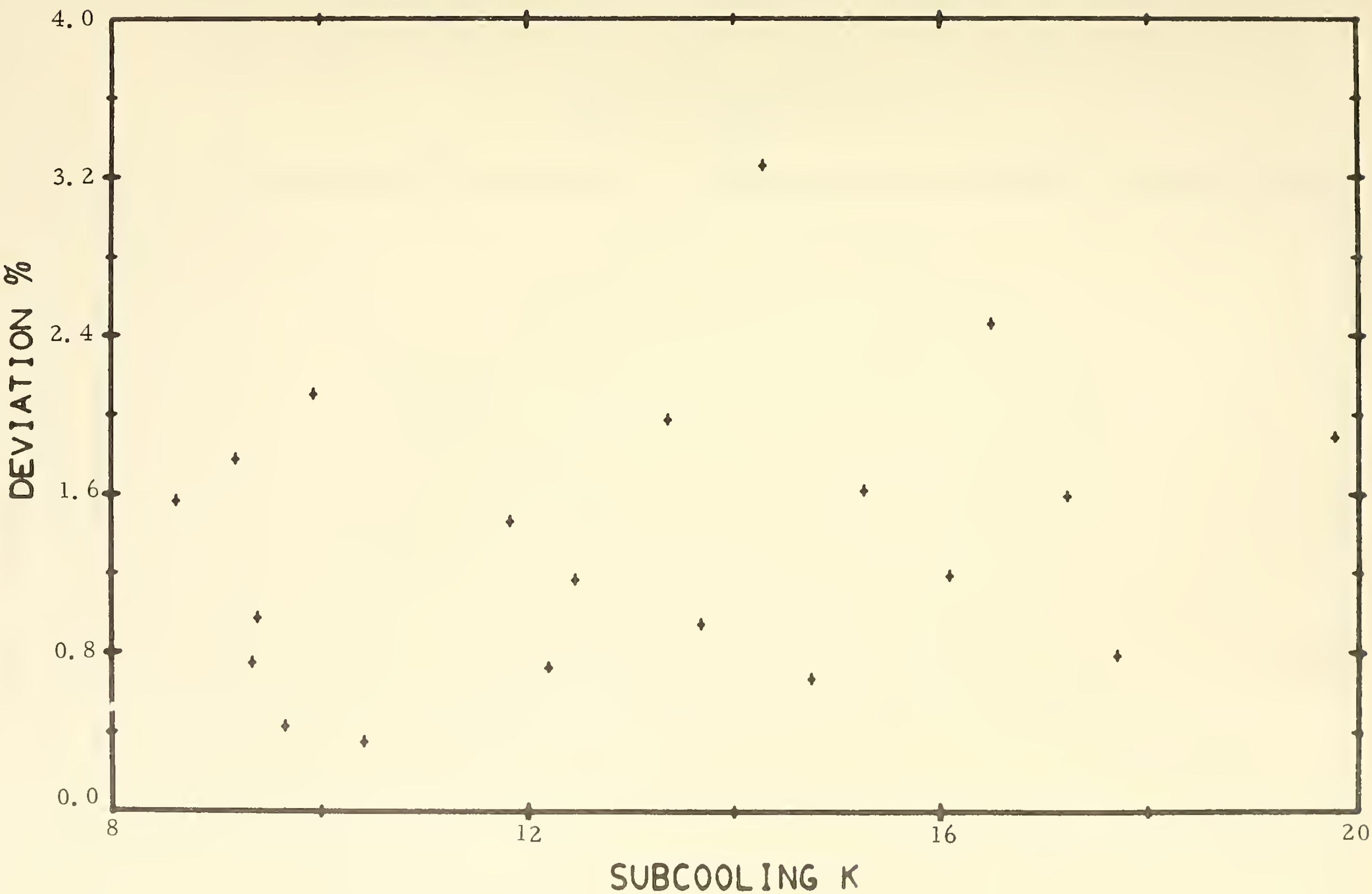

Figure 17E. Meter E, Performance vs. Subcooling, Second Rangeability Test.

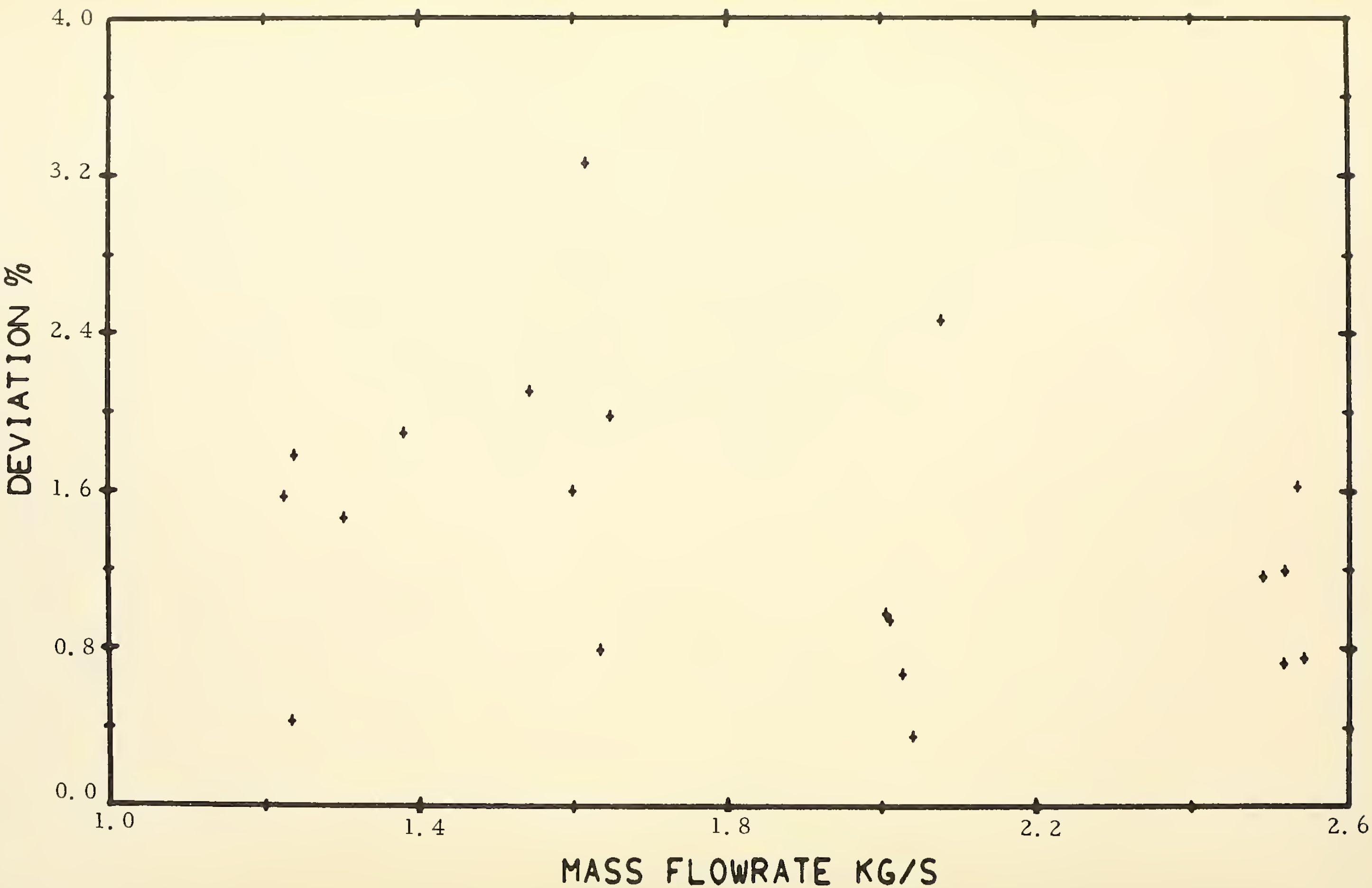

Figure 18E. Meter E, Performance vs. Mass Flow Rate, Second Rangeability Test.

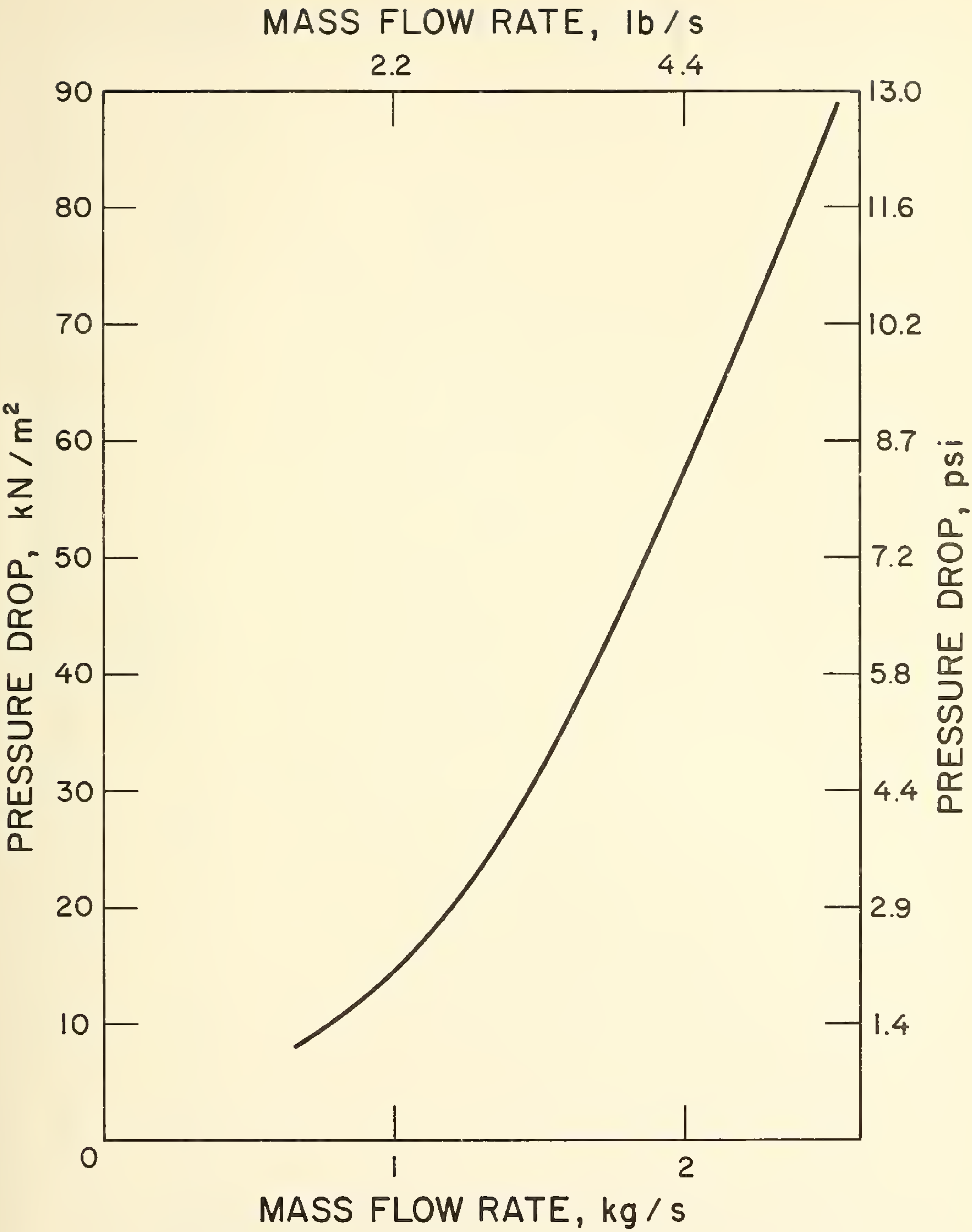

Figure 19E. Meter E Pressure Drop.

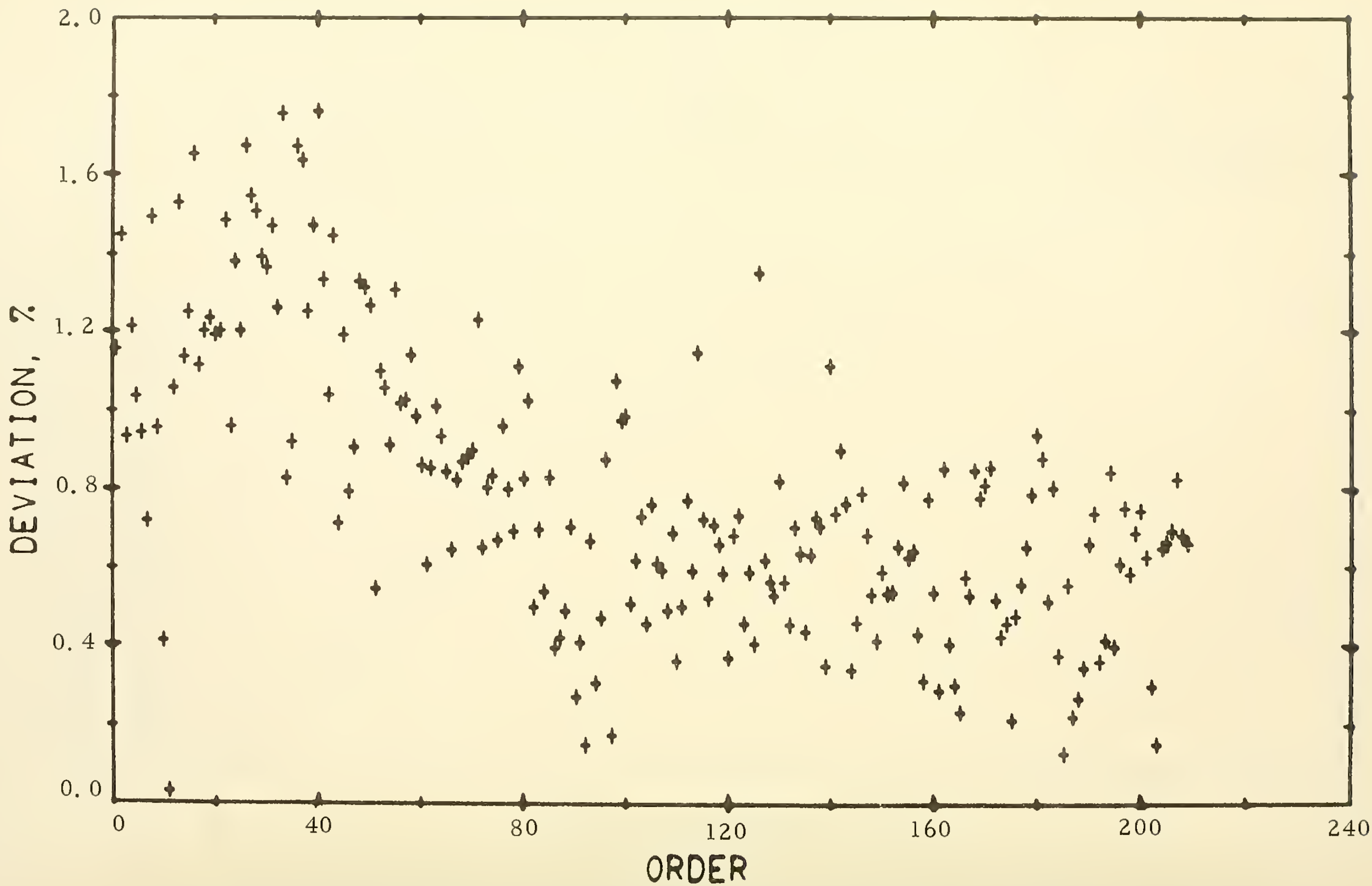

Figure 20E. Meter M, Performance Data from all Tests.

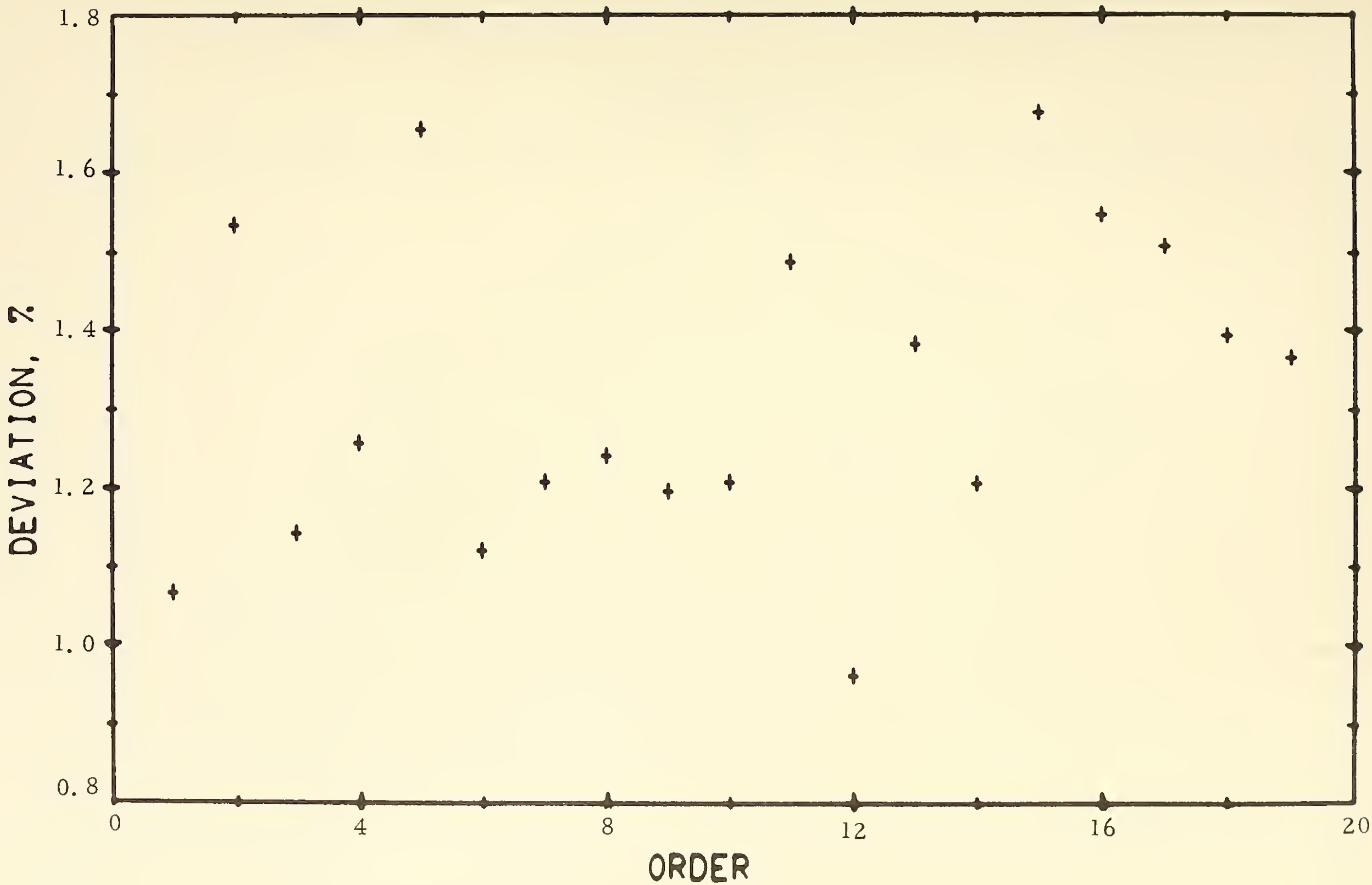

Figure 21E. Meter M, Performance vs. Order, First Rangeability Test.

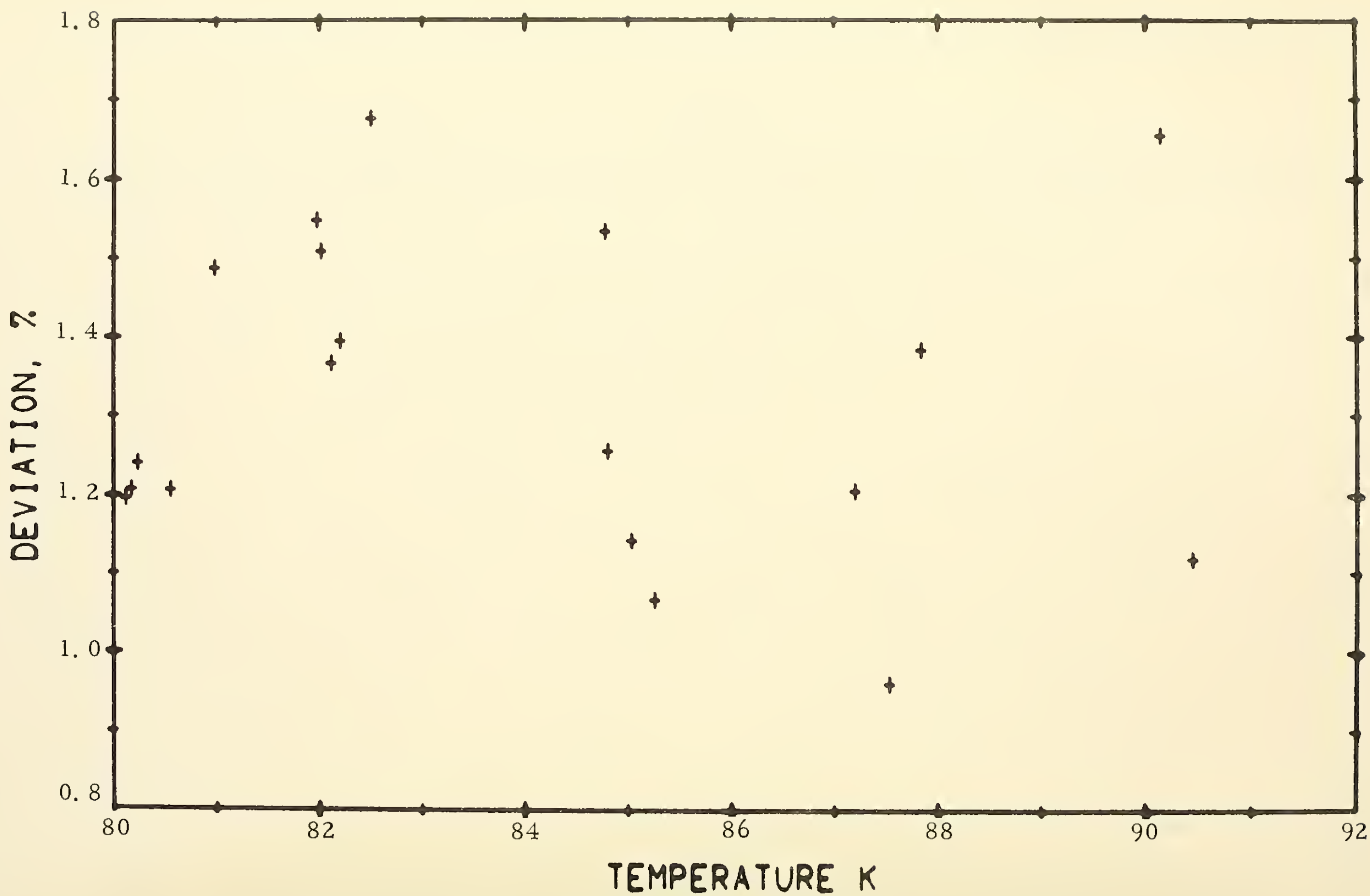

Figure 22E. Meter M, Performance vs. Temperature, First Rangeability Test.

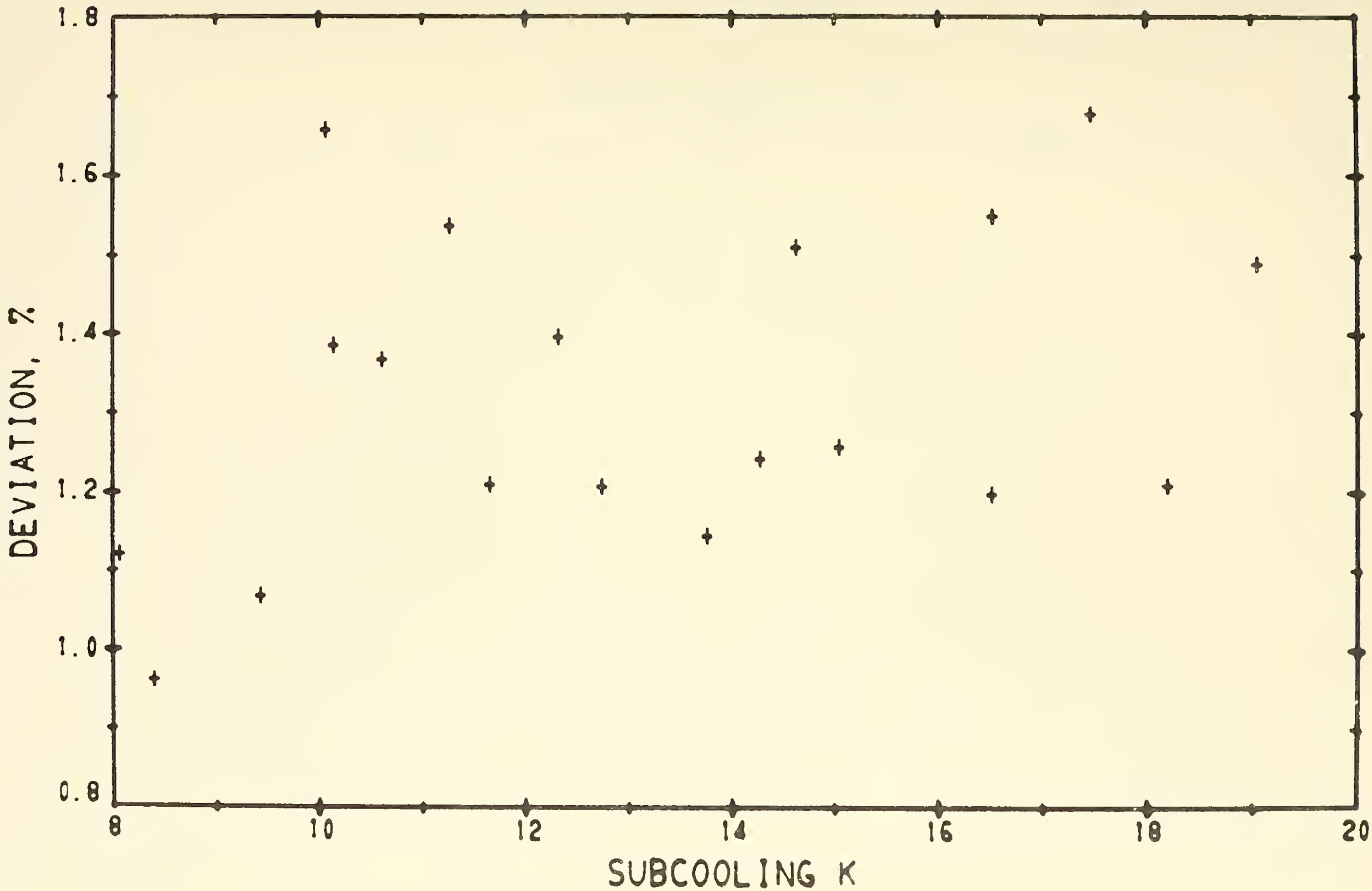

Figure 23E. Meter M, Performance vs. Subcooling, First Rangeability Test.

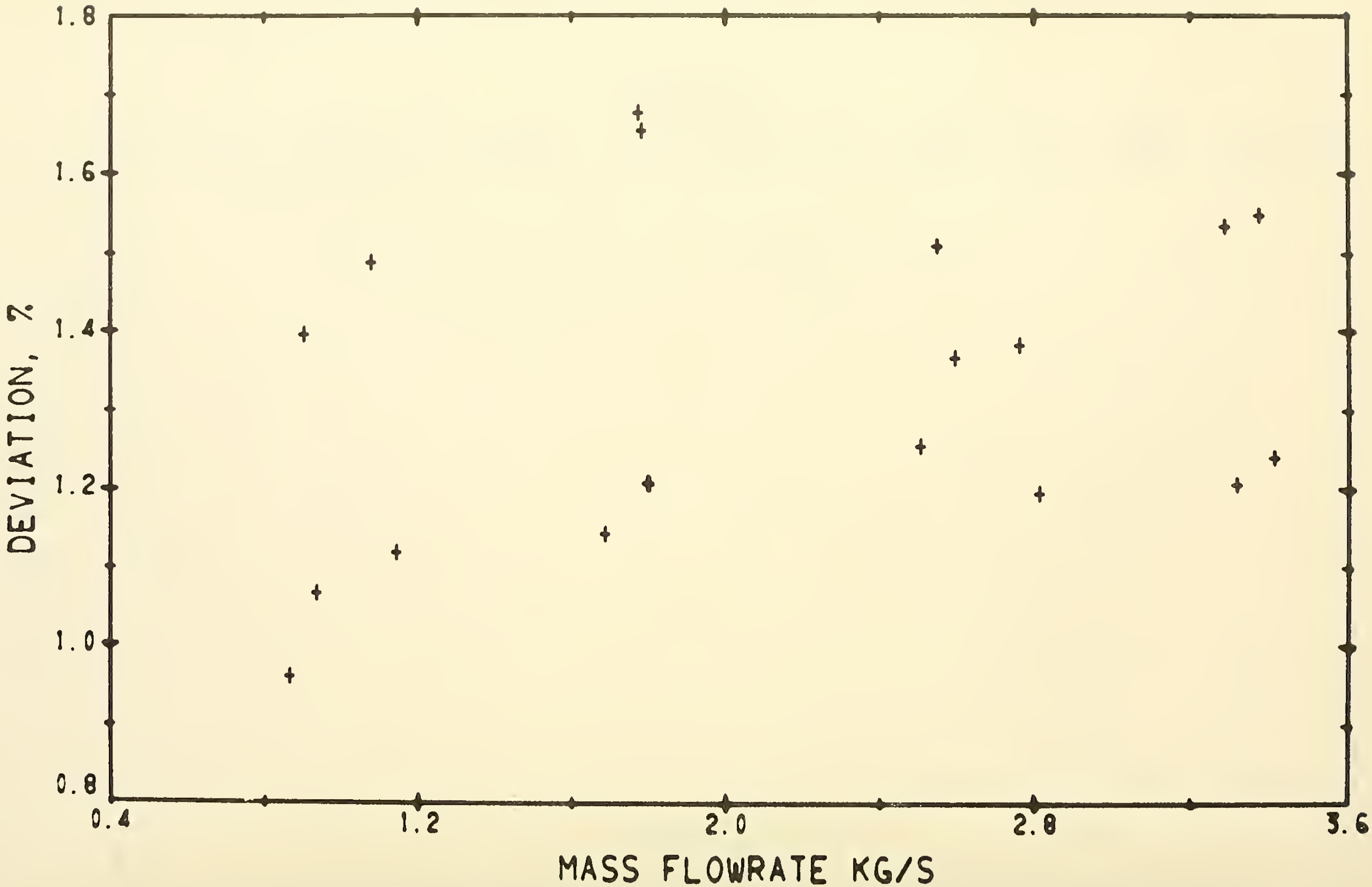

Figure 24E. Meter M, Performance vs. Mass Flow Rate, First Rangeability Test.

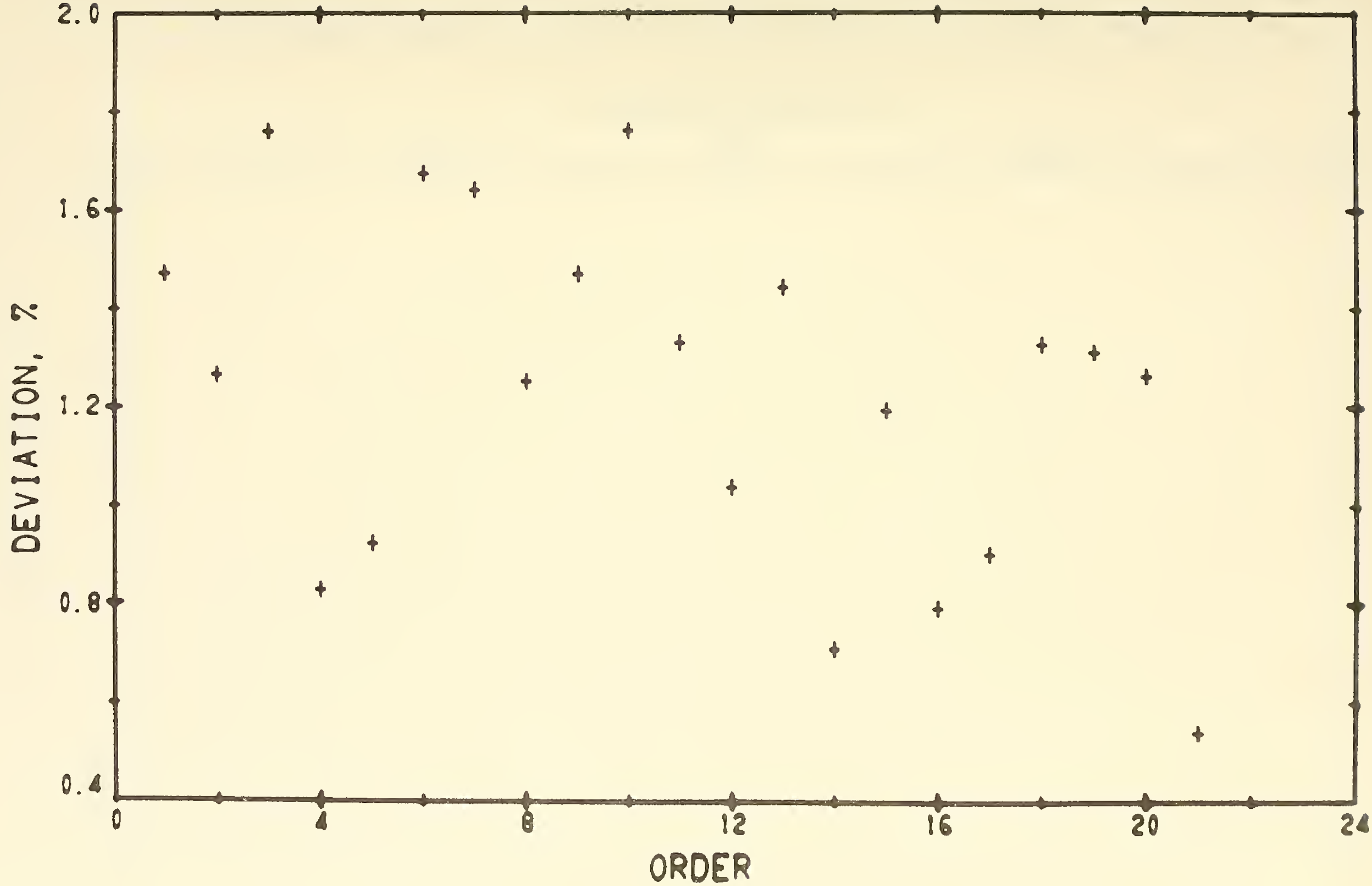

Figure 25E. Meter M, Performance vs. Order, Boundary Test.

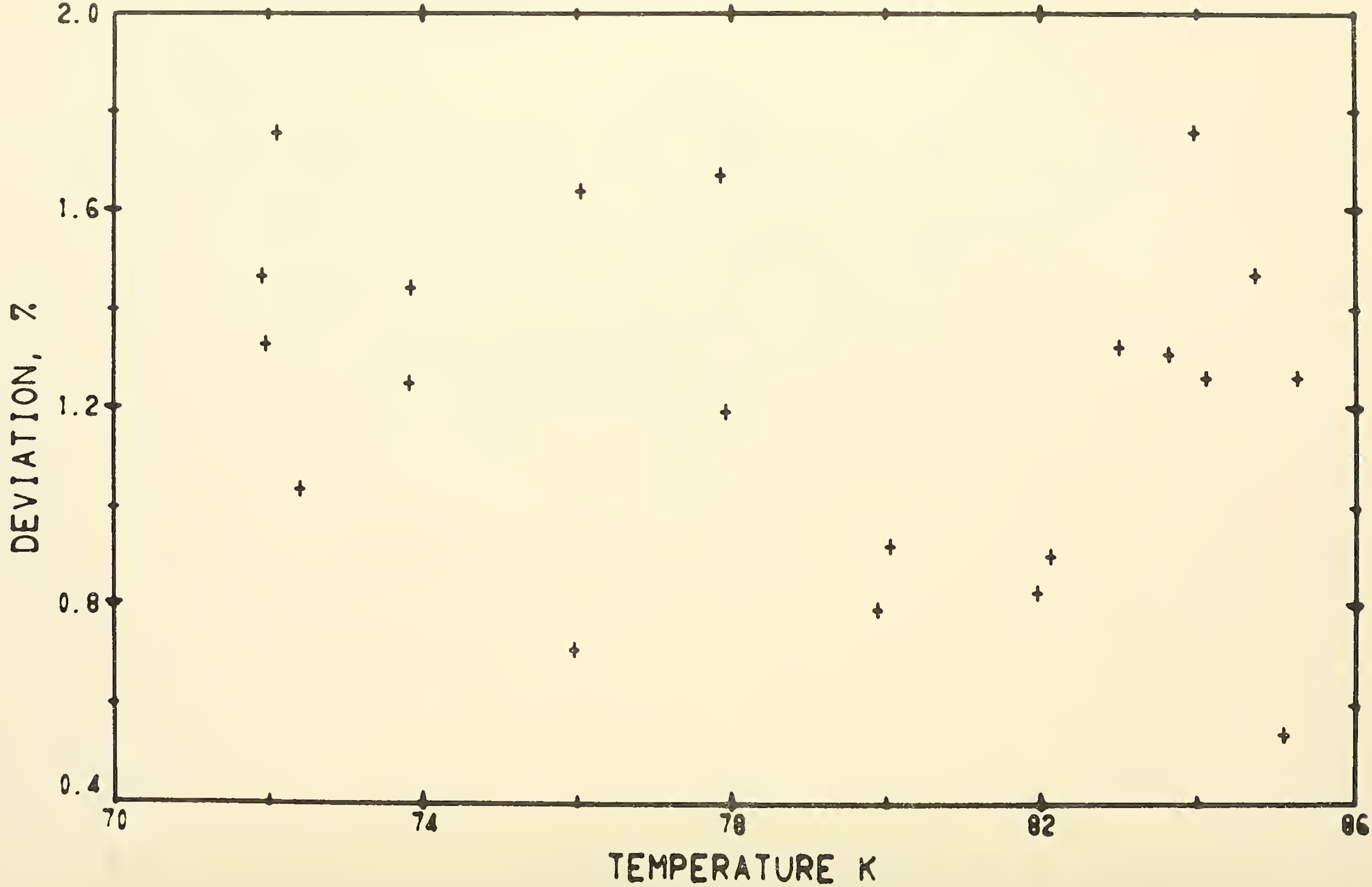

Figure 26E. Meter M, Performance vs. Temperature, Boundary Test.

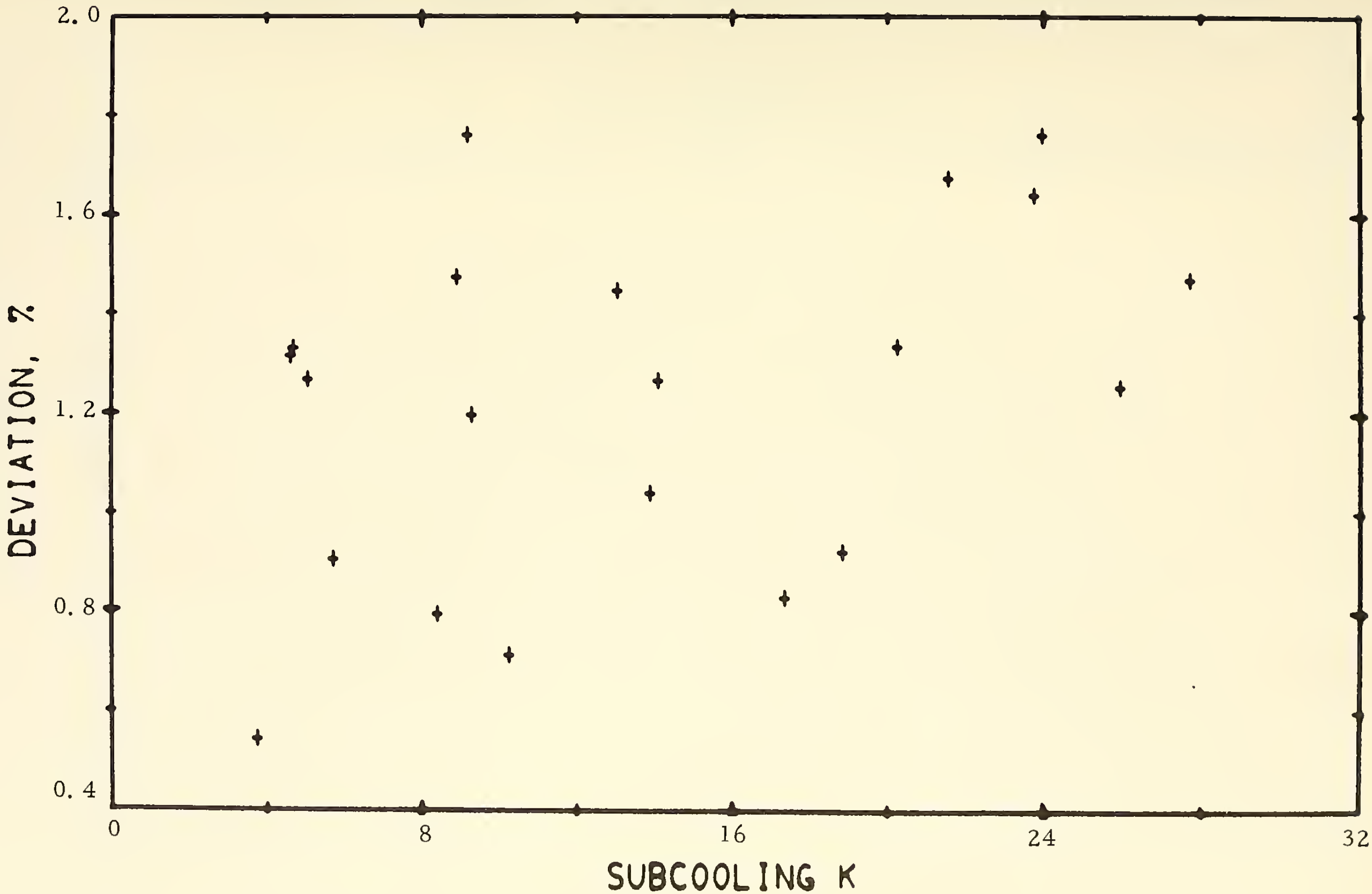

Figure 27E. Meter M, Performance vs. Subcooling, Boundary Test.

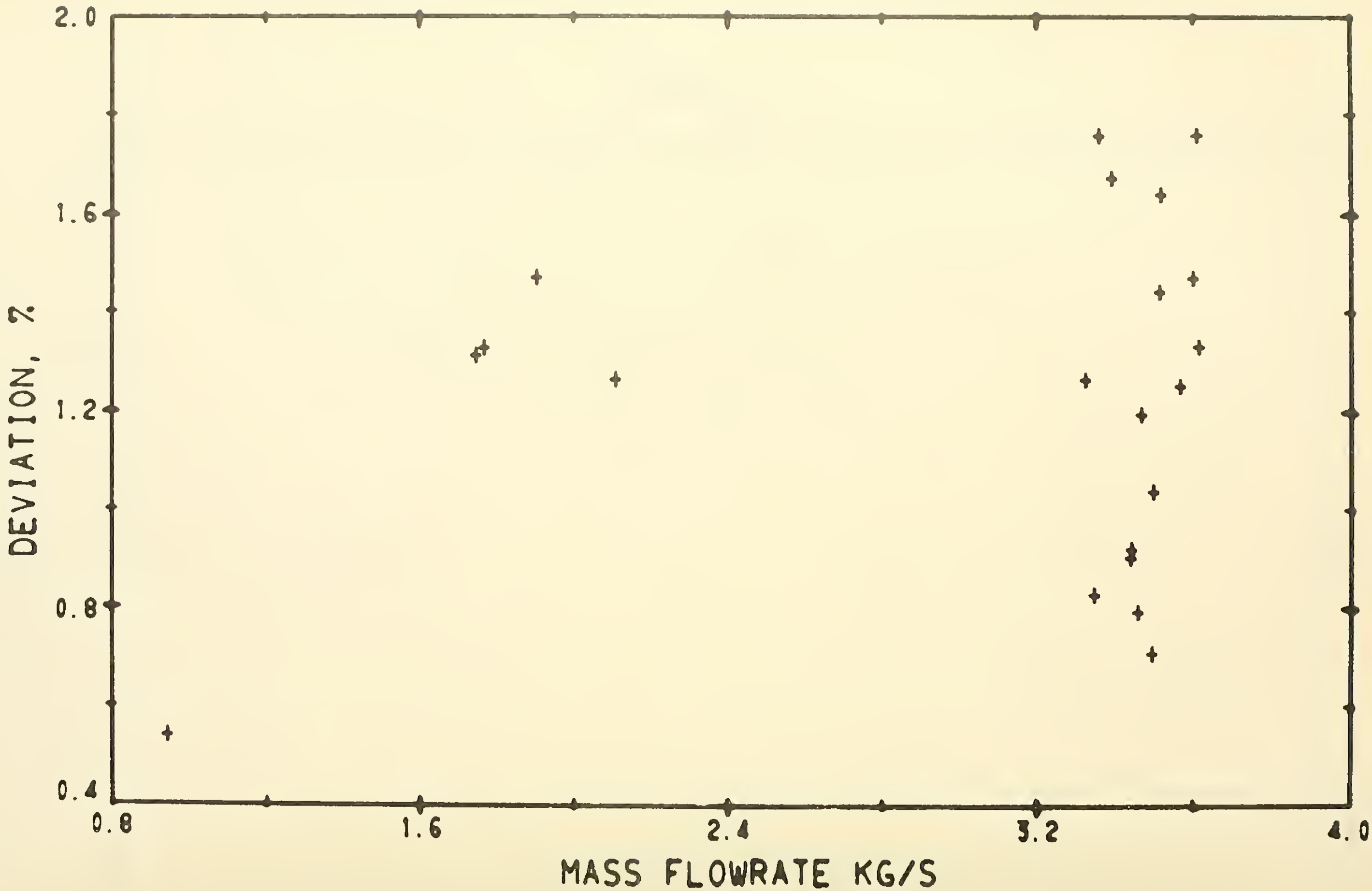

Figure 28E. Meter M, Performance vs. Mass Flow Rate, Boundary Test.

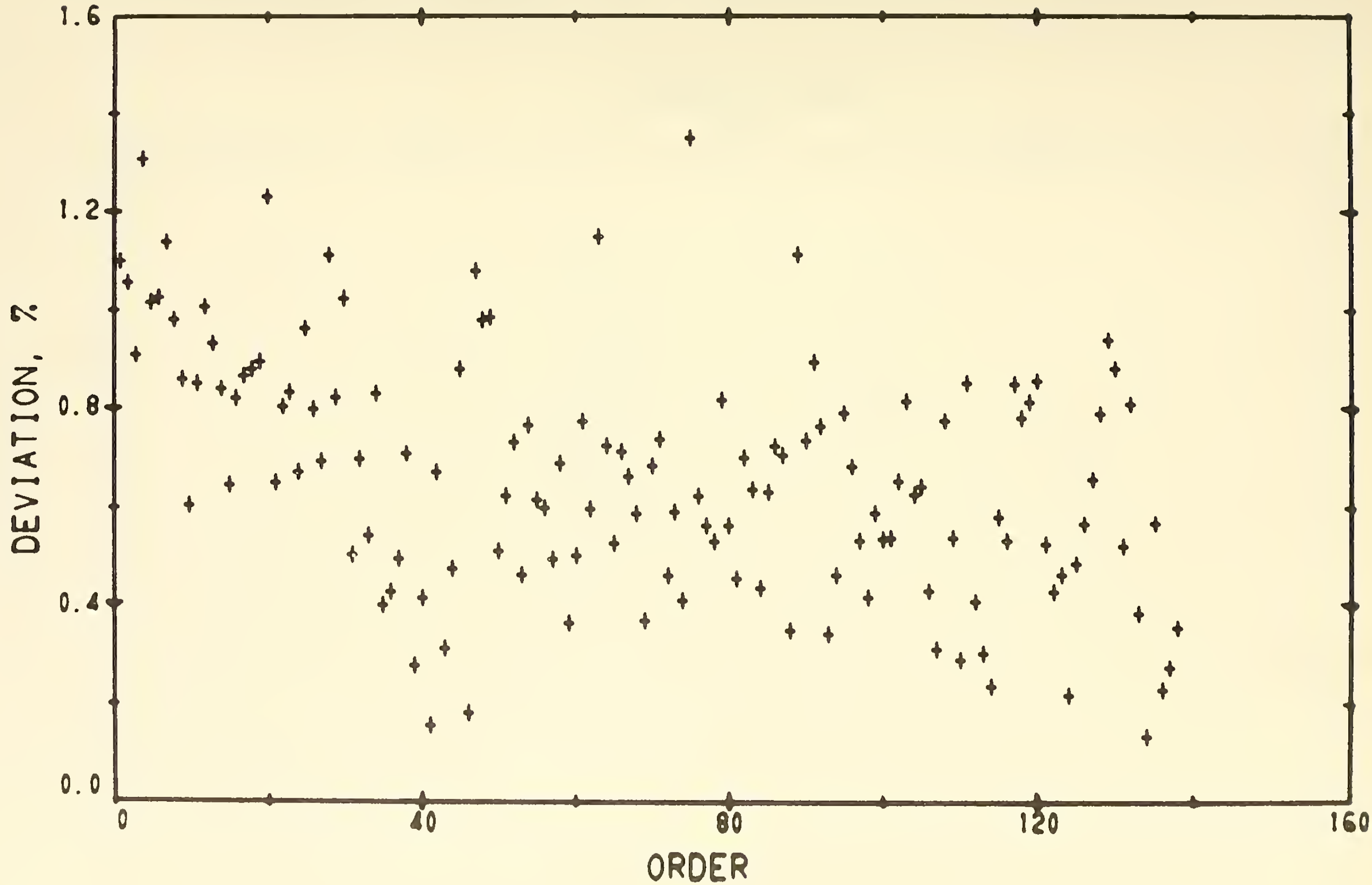

Figure 29E. Meter M, Performance vs. Order, Stability Test.

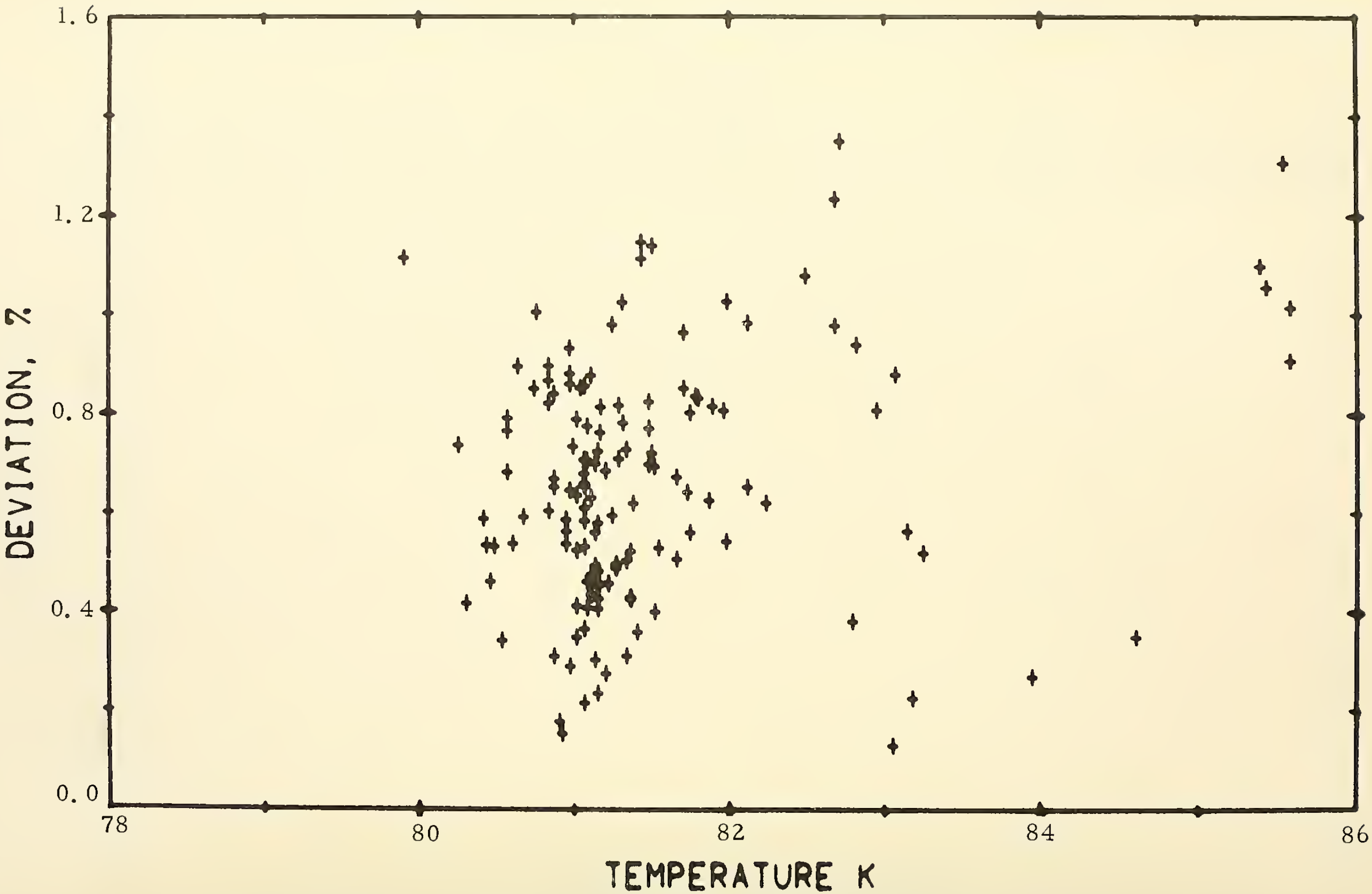

Figure 30E. Meter M, Performance vs. Temperature, Stability Test.

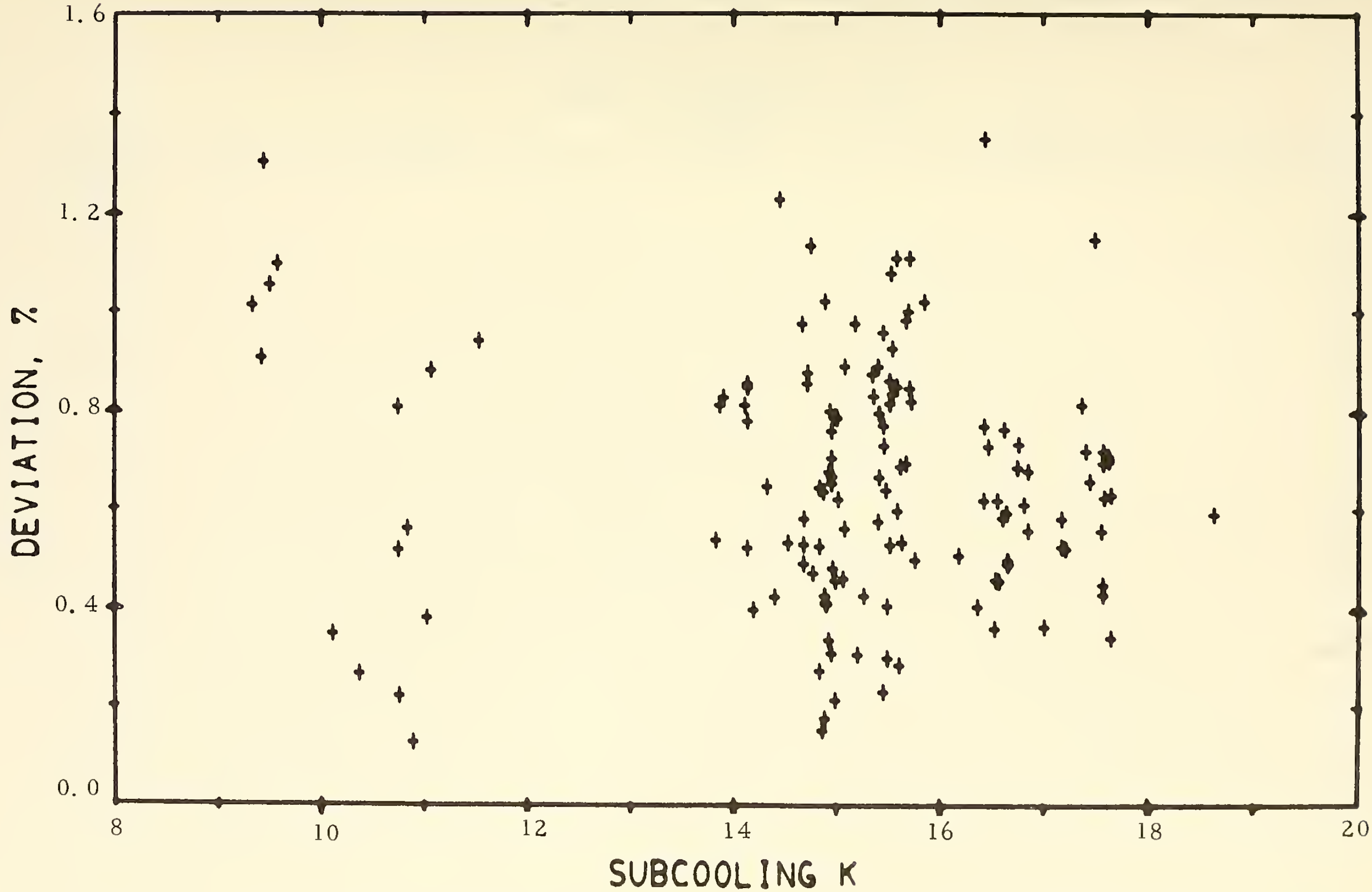

Figure 31E. Meter M, Performance vs. Subcooling, Stability Test.

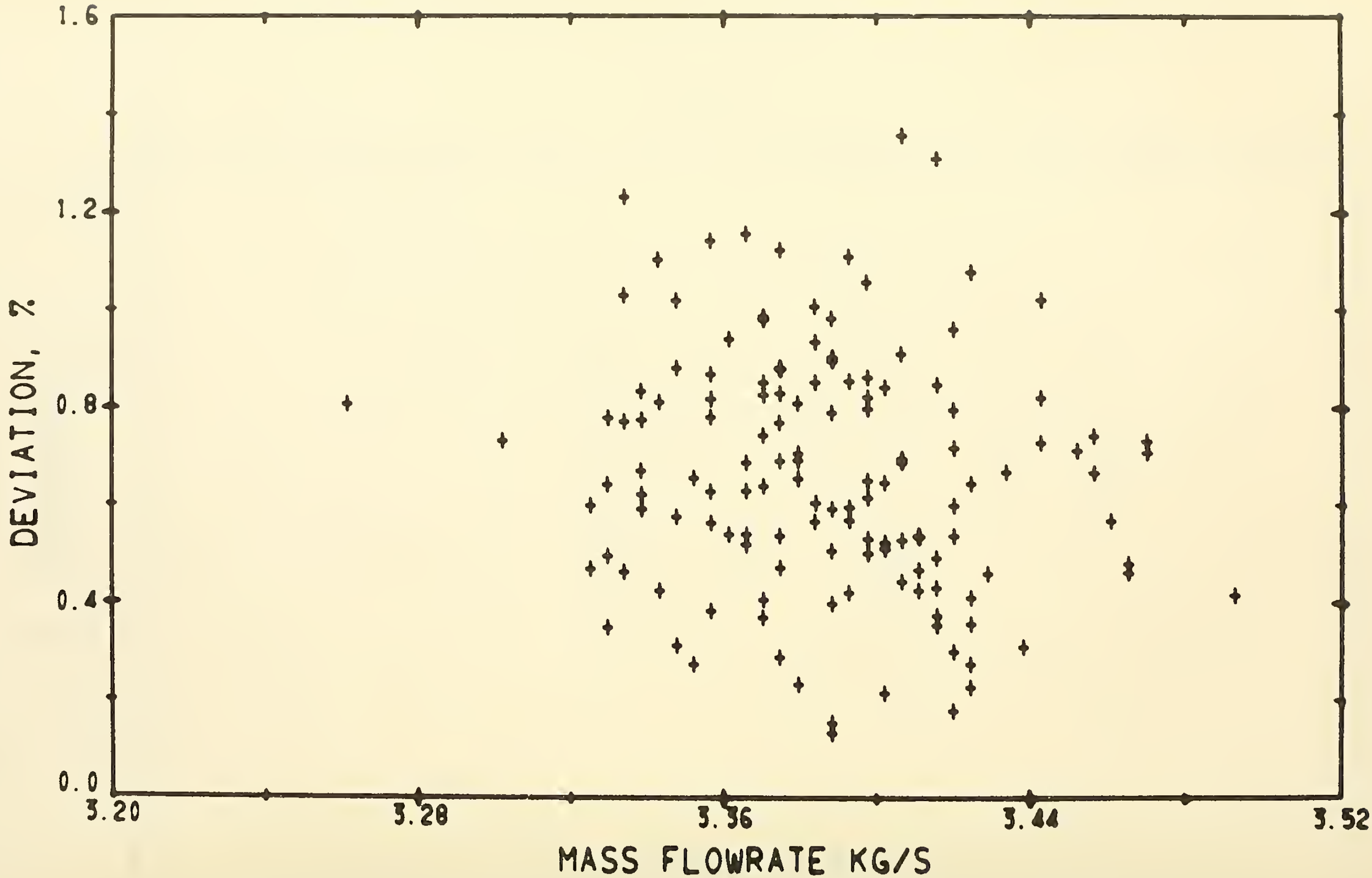

Figure 32E. Meter M, Performance vs. Mass Flow Rate, Stability Test.

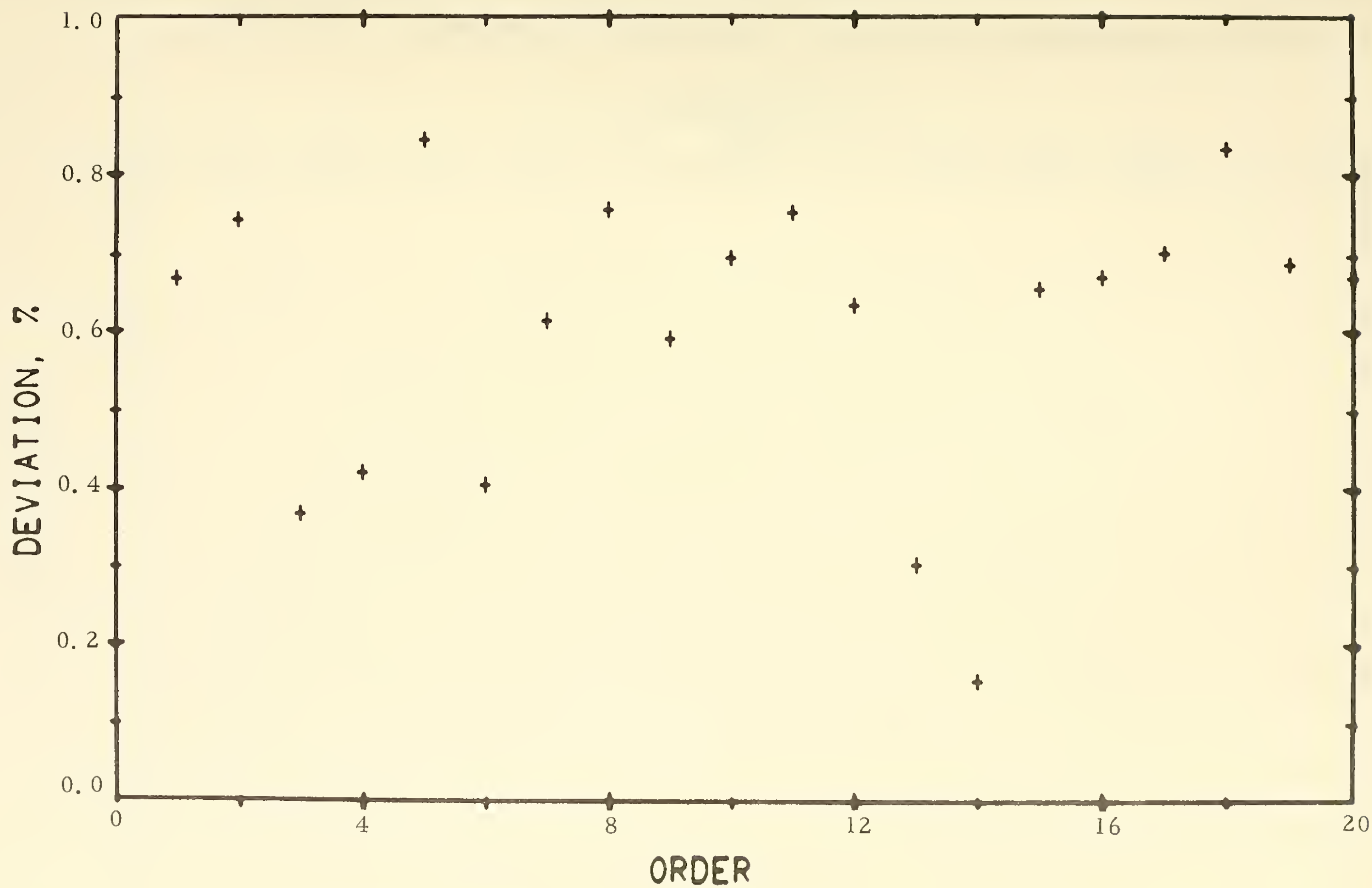

Figure 33E. Meter M, Performance vs. Order, Second Rangeability Test.

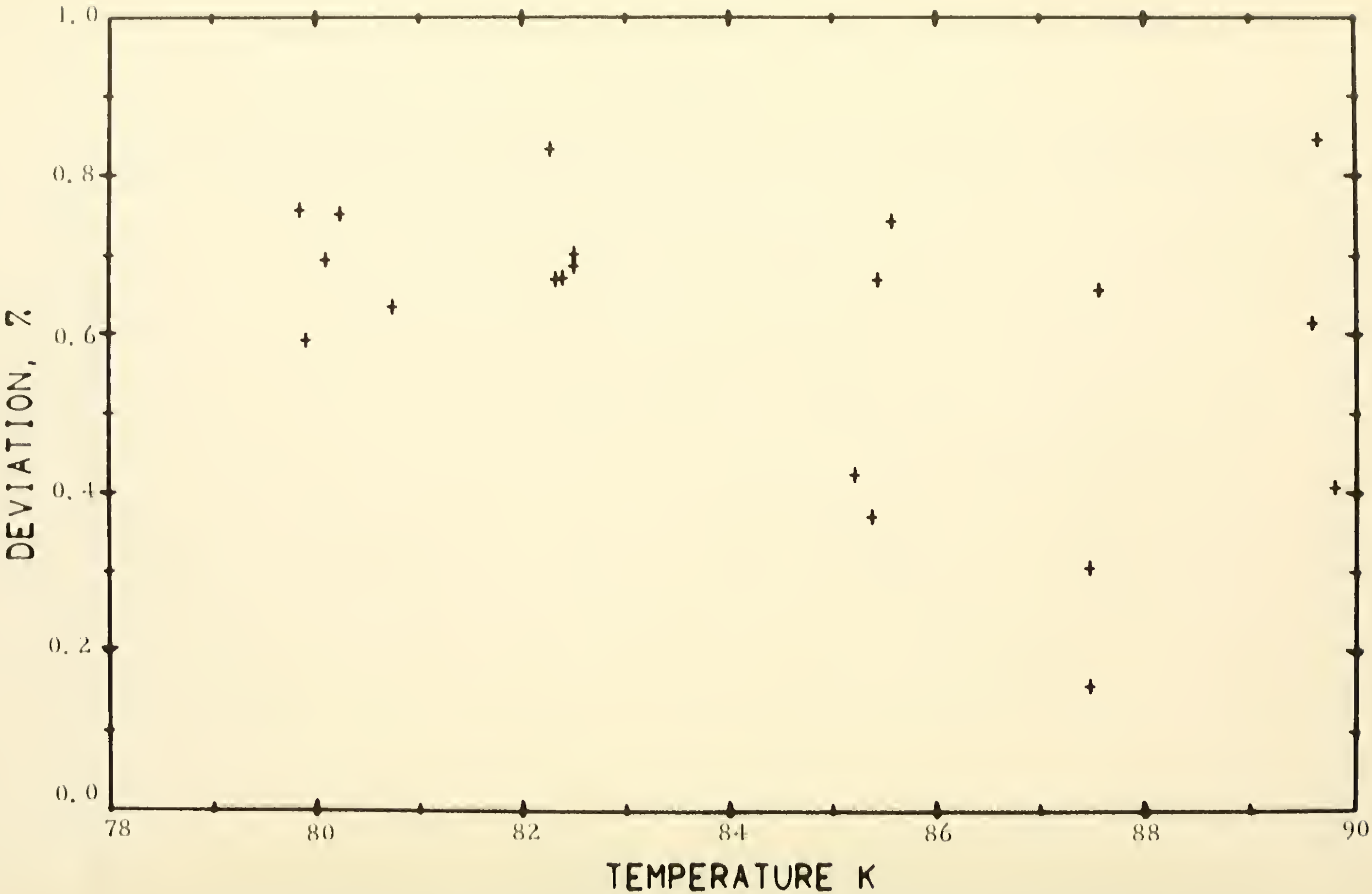

Figure 34E. Meter M, Performance vs. Temperature, Second Rangeability Test.

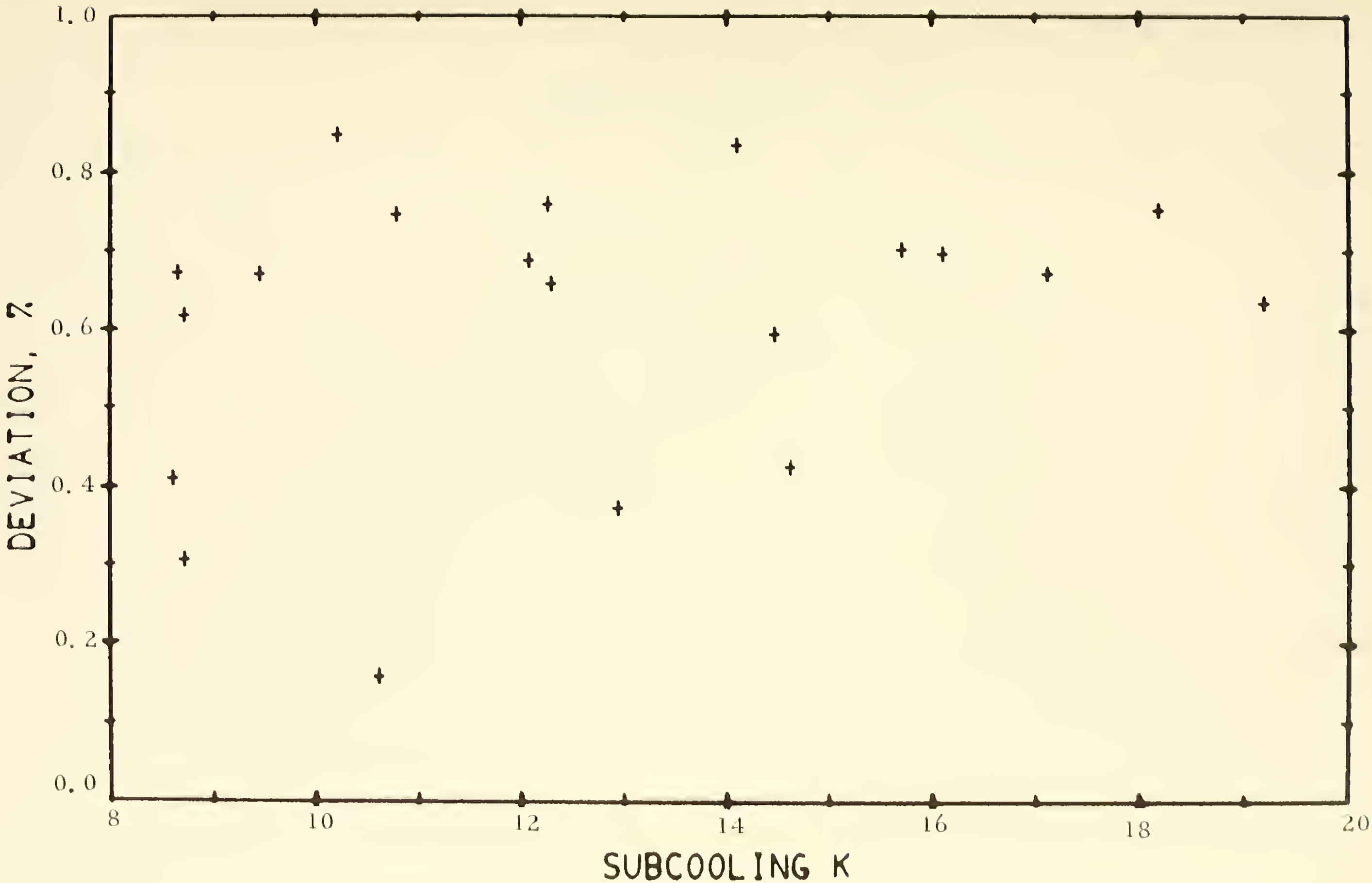

Figure 35E. Meter M, Performance vs. Subcooling, Second Rangeability Test.

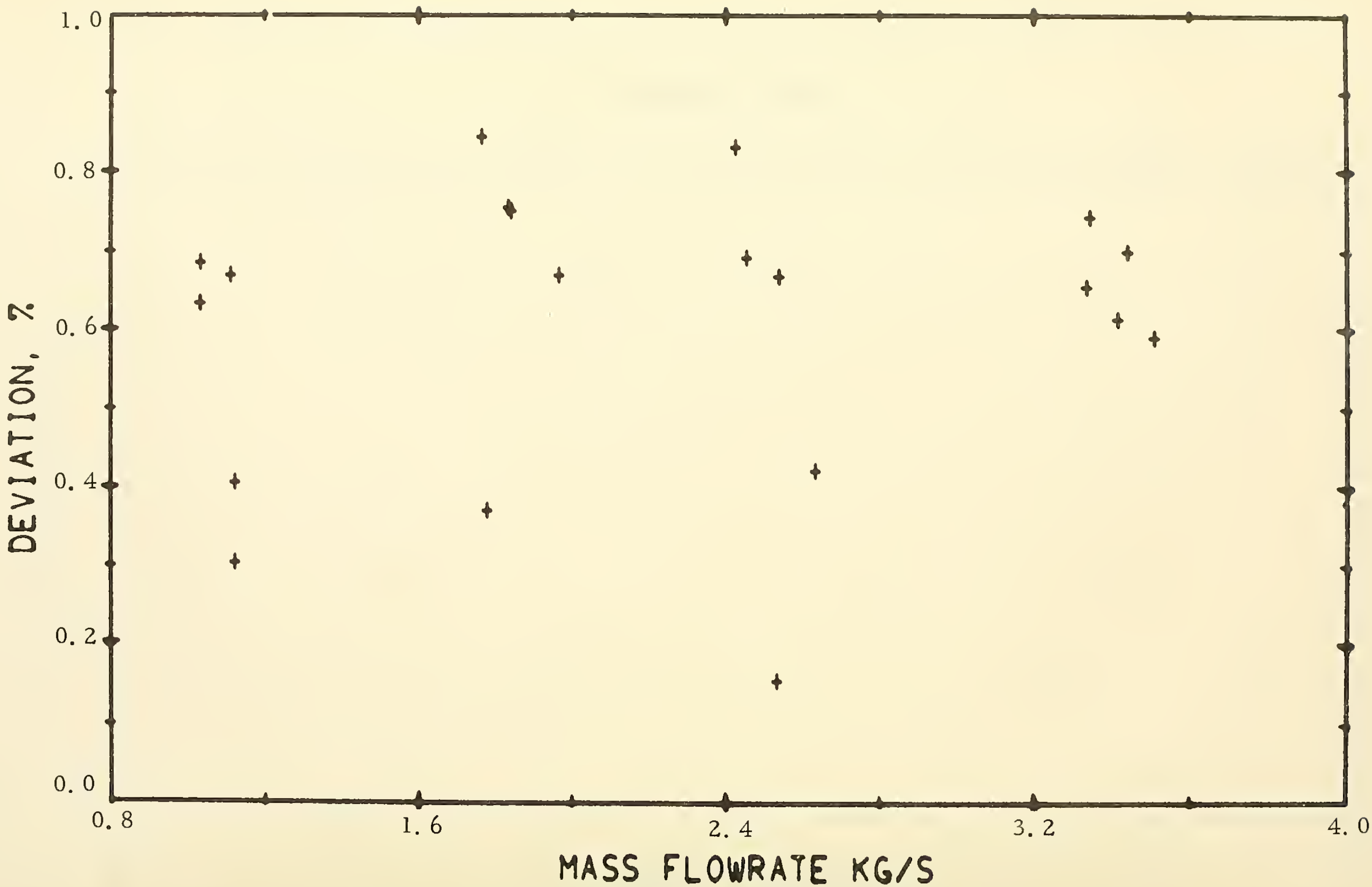

Figure 36E. Meter M, Performance vs. Mass Flow Rate, Second Rangeability Test.

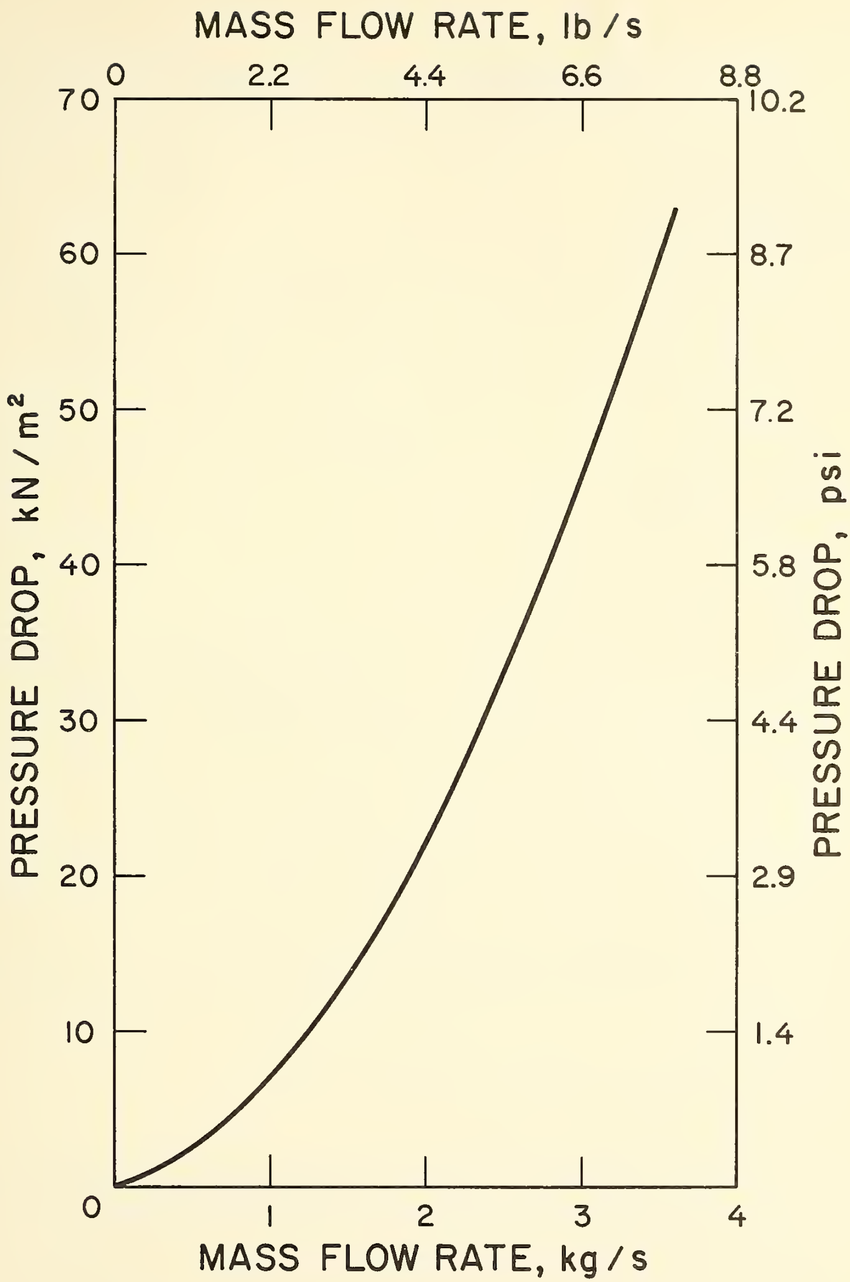

Figure 37E. Meter M Pressure Drop.

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15. SUPPLEMENTARY NOTES

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

The National Bureau of Standards (NBS) and the Compressed Gas Association (CGA) have jointly sponsored a research program on cryogenic flow measurement. A cryogenic flow research facility was constructed and was first used to evaluate commercially available cryogenic flowmeters operating on a positive displacement principle.

The operation and the accuracy of the flow facility is briefly described. The performance of the flowmeters on liquid nitrogen is described by reporting the precision and bias of the meters before and after an 80-hour stability test and by defining the existence of temperature, flow rate, subcooling, and time order (wear) dependencies.

Meters were evaluated with flow rates ranging from 0.00126 to 0.0063 m^3/s (20 to 100 gpm), pressures ranging from 0.34 to 0.69 MN/m^2 (50 to 100 psig), and with temperatures ranging from 72 to 90 K.

17. KEY WORDS (Alphabetical order, separated by semicolons)

Cryogenic; flow; flowmeters; liquid nitrogen; measurement; positive displacement.

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